DECISION SUPPORT SYSTEM FOR THE INTEGRATION OF SUSTAINABLE PARAMETERS IN SINGLE-FAMILY HOUSING PROJECT DELIVERY

A Dissertation
Presented to
The Academic Faculty

By

Silvia Juliana Tijo Lopez

In Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy in the
School of Building Construction

Georgia Institute of Technology

August, 2019

DECISION SUPPORT SYSTEM FOR THE INTEGRATION OF SUSTAINABLE PARAMETERS IN SINGLE-FAMILY HOUSING PROJECT DELIVERY

Approved by:

Dr. Daniel Castro-Lacouture, Advisor
School of Building Construction
Georgia Institute of Technology

Dr. Emanuele Massetti
School of Public Policy
Georgia Institute of Technology

Dr. Jason Brown
School of Architecture
Georgia Institute of Technology

Dr. Eunhwa Yang
School of Building Construction
Georgia Institute of Technology

Dr. Xinyi Song
School of Building Construction
Georgia Institute of Technology

Date Approved: July 25, 2019

To my husband Jarrett and my son, Samuel, for their love and support.

In memory of our little angel, Gabriel.

ACKNOWLEDGEMENTS

First, I greatly thank my advisor, Dr. Daniel Castro-Lacouture, for his continuous support, patience, and guidance. I cannot imagine a better advisor and mentor for my Ph.D. studies.

I sincerely extend my appreciation to committee members Dr. Emanuele Massetti, Dr. Xinyi Song, Dr. Eunhwa Yang, and Dr. Jason Brown, for taking the time to serve on my dissertation committee and providing valuable research insight to improve this work.

I also thank the College of Design faculty, especially Rick Porter, Fried Augenbroe, Michael Gamble, Russell Gentry, and Debbie Phillips, for sharing their knowledge and their genuine interest in students.

I am very grateful for the support provided by my family and friends; mainly, I thank my parents, sisters, my husband, and my husband's family.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

SUMMARY

The implementation of sustainable practices in building construction has a direct impact on the financial, environmental, and social dimensions of sustainable development. Powering and heating buildings consumes enormous amounts of energy, and the residential and commercial building sector remains the largest end-use sector for energy in the U.S. The fact that actual energy consumption of this sector is two-fifths of the total energy consumption in the United States represents a significant economic opportunity for the country.

In spite of the progress in performance and affordability of sustainable technologies, materials, and systems, the residential sector is behind in adopting these in single-family homes. Several building aspects must undergo evaluation under a holistic approach to achieving the technical and economic success of the project, but the fragmentation of the industry and the required expertise level for using existing simulating tools represent a barrier for this purpose.

In residential projects, the selection of design and construction parameters occurs mostly during the early stages of the pre-construction process, while the majority of the building simulation tools require information from late stages of the process. During the early stages, the designer cannot easily predict the impact of decisions on building performance and cost. Furthermore, existing methodologies do not integrate project goals in early stages (i.e., pre-design, conceptual design, and schematic design) of the pre-

construction process. Without these methodologies, selecting sustainable parameters for housing delivery and implementing sustainable principles is difficult, and consequently jeopardizes reaching sustainable goals for the building.

The result of this research is a decision support system (DSS) that uses the analytic hierarchy process (AHP) and system dynamics (SD) to assist decision makers in the selection of construction parameters for sustainable housing. The proposed DSS integrates a set of project goals in the process of selecting alternatives, allowing a balance between the preferences of the decision maker and the solution that better fits those preferences.

The approach focuses more on using DSS to support design exploration rather than finding optimal solutions. Given the iterative nature of the design process and the fragmentation of the construction industry, the proposed DSS provides information about costs, duration, and environmental impact of the alternatives at early stages of the project development. Therefore, an objective comparison of different design alternatives under identical conditions can take place, and the decision maker can learn from the effects of new decisions over other parameters that are interrelated. The outcomes of the research can help developers, architects, and home-owners to define sustainable parameters at early stages of the project delivery when the impact of their decisions is higher, and the cost of implementing changes is lower than in the later stages.

CHAPTER 1 INTRODUCTION

Humans have been building homes and structures for thousands of years. The way we live today is a result of the constant evolution of building construction as a human activity. The first buildings were temporary structures that provided humans with protection from the elements. Over time, the first rudimentary structures evolved into durable dwellings and builders created structures to provide drinking water to settlements making it possible to settle in homes and live nearby other people in large communities.

Building construction is an activity that developed with the use of materials and construction methods. Because of the primary need of dwellings that are durable and resistant to nature, the construction industry made it possible to build environments that are functional building structures for living, working, storage, and even recreation. At present, it is possible to have increasingly precise control over factors that affect human comfort indoors, such as air temperature, humidity, and lighting. This control requires materials and natural resources during the construction process, as well as for the maintenance and operation of the buildings. In fact, the residential sector contributes to 25% of the total energy consumption of the United States (EIA, 2018).

Since the residential sector greatly contributes to the overall energy consumption of the United States, it justifies paying close attention to the importance of implementing sustainable practices in the homebuilding industry. Likewise, the implementation of sustainable practices in residential construction has a large impact on the economic, environmental, and social dimensions of sustainable development.

Sustainable practices are an opportunity in the residential construction market. 71% of single-family builders and 57% of multifamily builders say consumers will pay more for green homes (Dodge, 2017). However, the integration of sustainable features in residential housing is far from being the norm in new construction projects in spite of the existence of computational tools and the availability of new construction materials. Researchers affirm that current tools are inadequate, complex, and user-hostile (Attia, Gratia, De Herde, & Hensen, 2012). Current tools require a high level of expertise (de Wilde & Van Der Voorden, 2004) and are costly in terms of money and time (Augenbroe, de Wilde, Moon, & Malkawi, 2004). During decision making, the designer cannot easily predict the impact of decisions on building performance and cost (Attia et al., 2012). Furthermore, existing tools do not integrate project goals or project conditions in early stages (i.e., pre-design, conceptual design, and schematic design) of the pre-construction process.

1.1 Sustainable housing

Today, home construction is a continuous activity due to population growth, changes in land cost, updates in building codes, and construction requirements. There are many considerations in building sustainable homes such as

- The energy and materials required for the construction, occupancy, maintenance, renovation, and demolishment of the house.
- The impact that the house has on the environment during its lifespan.
- The water demands.
- The end of lifespan and required resources for disposal and recycling of the remaining materials.

Different means fulfill the above considerations; one is the adequate selection of sustainable parameters in the early phases of the project delivery process. In this research, a definition of a sustainable parameter for a house project delivery is a factor forming a set of conditions for the design of a sustainable system. A review of previous studies about sustainable construction was used to identify the sustainable parameters in this research. As a result, the following categories were defined to group those sustainable parameters: location, orientation, building geometry, building envelope, arrangement and grouping of spaces, space conditioning, energy efficiency, water efficiency, renewable energy, and life cycle cost.

1.2 Decision support system

A decision support system (DSS) is an interactive computer-based system that aids decision makers with data and models to solve unstructured problems (Sprague Jr, 1980). DSSs assist people with making decisions about problems that rapidly change and are vaguely specified — i.e., unstructured and semi-structured decision problems. Lastly, decision support systems are computer-based, human-powered, or a combination of both.

This research proposes an approach that helps decision makers to select sustainable parameters for the construction of single-family housing projects as a response to the limited integration of sustainable features in residential construction. The scope of this project specifically addresses single-family detached homes located in the metro Atlanta area. An outcome of this approach is the design and validation of an exploration DSS tool to use during the early stages of the pre-construction phases of the housing project delivery processes. As a result, the development of a DSS for the selection of sustainable parameters in the project delivery process might incentivize implementing sustainable practices in new housing construction.

1.3 System dynamics

System Dynamics (SD) is a branch of system thinking, a way of understanding reality that emphasizes the relationships among system parts, rather than the properties of the parts themselves. System thinking is non-linear and organic; it helps identify structures, patterns, and events that underlie complex situations. The SD approach solves the problem of simultaneity (mutual causation) by updating all variables in small increments of time. Positive and negative feedbacks and time delays structure variable interactions and control (Hjorth & Bagheri, 2006).

Various software packages for model solving can graphically represent a dynamic system. Furthermore, as previous research shows, a variety of applications in the fields of civil engineering and building construction use SD modeling (Tijo-Lopez & Castro-Lacouture, 2016). Previous works show the capability of using an SD model to support the decision-making process of construction method selection with sustainable considerations (Ozcan-Deniz & Zhu, 2016).

1.4 Motivation

The increased awareness of environmental problems that affect the built environment has led to research on sustainable practices in the construction industry. A large part of this trend concerns developing computational tools for modeling, designing, and analyzing any building, including houses. Despite increased interest in sustainable development, only a small percentage of existing housing projects align with all aspects of sustainability.

The McGraw-Hill study of Green Multifamily and Single Family Homes from 2014 (Bernstein & Russo, 2014) estimated that only 9.3 percent of new multifamily and single-family homes were green. According to this report, single and multifamily housing projects account for 45 percent of the value of all US construction projects started in 2014.

Until recently, the call for sustainability has been voluntary rather than mandatory. Some governments found that this voluntary call is insufficient. In Europe, the recast of the Directive on the Energy Performance of Building (EPBD) imposes adopting measures that improve energy efficiency in buildings to reach the objective of rating all new buildings as a nearly zero energy building (nZEB) by 2020 (Ferrara, Fabrizio, Virgone, & Filippi, 2014).

Adopting sustainable practices is an opportunity for homebuilders because of the perception of consumers regarding green homes. Builders and remodelers of single-family and multifamily sectors report that the market recognizes the value of green; i.e., 73 percent of single-family builders and 68 percent of multifamily builders say consumers will pay more for green homes (Bernstein & Russo, 2014).

1.5 Purpose statement

The purpose of this research is to develop a decision support system (DSS) that assists decision makers with selecting construction parameters in single-family housing project delivery. The approach focuses on working with SD as a tool to support design exploration. Given the iterative nature of the pre-construction process and fragmentation of the construction industry, DSS will lead decision makers in the process of accomplishing project goals. The proposed system provides information from the selection of sustainable parameters about cost, duration, and environmental impact. Therefore, an objective comparison of different design options under identical conditions is possible, and the decision maker can learn from the effects of new decisions over other interrelated parameters.

The pre-construction of a sustainable housing project, which consumes time and human resources, is an iterative process that requires experts from different fields. Currently, there is a gap in methodologies, which integrate project goals and conditions, in the selection of sustainable parameters for housing delivery at the early stages of the pre-construction phase. Studies describing the selection of sustainable construction components in local housing projects and building simulation tools that support the selection are also unavailable.

1.6 Research questions and objectives

1.6.1 Research questions.

Based on the purpose statement, the research questions are:

1. Is it possible to use system dynamics (SD) to create a decision support system that assists decision makers in the selection of sustainable parameters during the early stages of the pre-construction process of residential projects?
    a. Is it possible to include project goals of decision makers in the selection of sustainable features?
    b. Is SD the appropriate approach for residential construction projects?
    c. Does SD show the effects of a decision on other interrelated parameters?

Hypothesis: The use of SD supports the selection of sustainable parameters based on the integration of project goals and external factors, and it allows the identification of complex interactions among different elements of the model.

2. What impact do preferences of decision makers have on determining the selection of sustainable features?
    a. What are the effects of the selection of parameters on the total construction cost, duration, and environmental impact?
    b. How do preferences affect the selection of sustainable features at the early stages of the pre-construction phase?

Hypothesis: The proposed method helps decision makers during the pre-construction phase by showing the effect of changes that create different preferences over the selection of alternatives.

1.6.2 General objective.

The general objective of this research is to formulate a decision support system that assists decision makers in the selection of sustainable parameters in single-family housing project delivery. The proposed system integrates the preferences of decision makers and provides information about cost, duration, and environmental impact resulting from the selection of building components. Therefore, this work will include an objective comparison of different design options under identical conditions.

1.6.3 Specific objectives.

The specific objectives of this research are:

- To propose an analytic procedure for housing project delivery to study the effect of different project conditions.
- To create a database of sustainable features that describes economic, environmental, and construction-time characteristics and allows comparing different scenarios.
- To design a system dynamics model that integrates external information from the environment and preferences of stakeholders with a calculation procedure.
- To develop and validate a support strategy for the selection of sustainable parameters in housing project delivery.

1.7 Document outline

Eight chapters divide this dissertation. Chapter 1 introduces the problem and the approach used to address it. Chapter 2 provides a background on sustainable construction and current standards and rating systems for sustainable housing. Chapter 3 reviews literature related to previous research on energy, materials, and water for sustainable construction. Chapter 4 reviews the impact of buildings in resource consumption and then focuses on the integration of sustainable parameters in housing project delivery.

Chapter 5 covers the initial development of the decision support system and explains the structure of the system. Chapter 6 covers the further development and baseline run of the prototype SD model. Chapter 7 presents the results of this prototype model and discusses these results and the process for the use of the model. Finally, Chapter 8 presents future improvements to and applications of the model, potential for future research, and conclusions.

CHAPTER 2 SUSTAINABLE CONSTRUCTION CONTEXT

2.1 Building life cycle

Building construction involves a series of processes that are associated, directly or indirectly, with creating structures to satisfy specific human activities. Pre-construction, construction, occupancy and maintenance, and end of life are the four main phases in a simplified representation of a typical life cycle of a building. An analysis of the individual role of each phase in the life cycle of a construction project is possible. Figure 1 presents a basic scheme of a typical building life cycle.

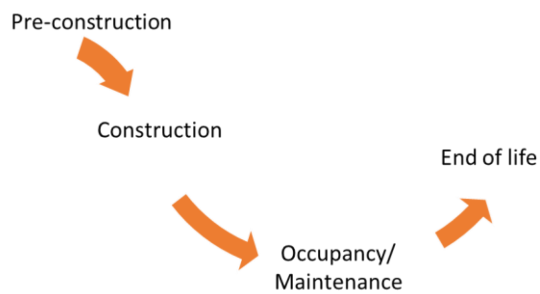


Figure 1. Building life cycle

Important decisions take place during the early phase of project pre-construction. Furthermore, the following six stages subdivide the design process into predesign, conceptual design, schematic design, design development, construction documents, and bid negotiation. An important deliverable of the pre-construction phase is the set of construction documents to build the project during the construction phase.

The pre-construction results materialize in the construction phase, which consumes a vast amount of resources on site (e.g., capital, human, and natural resources). The processed materials that remain as part of the building during its entire life cycle also consume a vast amount of natural resources.

After completing the construction phase, a project is suitable for occupancy. Occupancy and maintenance are typically the longest phases of the life cycle of a building, and although lifespans of buildings vary, lifespans are usually more than 50 years. Furthermore, proper maintenance, repairs, remodeling, additions, and retrofitting extend the lifespan of a building.

Finally, a building reaches the end of its life cycle when it is no longer suitable for its original purpose due to obsolescence or risk to human life or property. The end of the life cycle often leads to the process of Demolition and Disposal or the process of Deconstruction and Material Reuse.

2.2 Material life cycle

The greatest consumption of resources throughout the life cycle of a building occurs during the construction phase and the occupancy and maintenance phase. During construction and operation of the building's lifetime, buildings consume many types of resources such as land, materials, water, energy, and ecosystems.

The rate of material consumption for a typical building reaches its peak during construction. Figure 2 is a representation of the material life cycle, and it shows that the life cycle of materials begins before the life cycle of the building, extending beyond the building's end-of-life. The quantification of material usage takes into consideration total cost, total volume, or the embodied energy. This latter measurement is a ratio between the consumption of resources during the construction phase and the occupancy and maintenance phase.

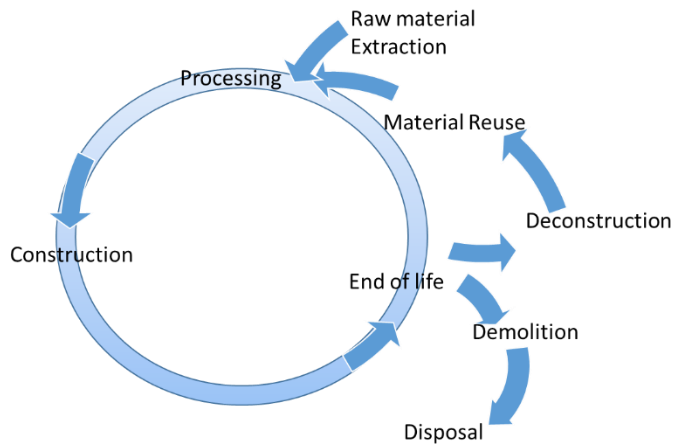


Figure 2. Material life cycle in building construction

Embodied energy, in the context of buildings, is the energy consumption of all processes associated with the production of a building, which extends from raw material extraction to processing, transport, and product delivery. Sartori and Hestnes (2007) conducted a literature survey on 60 buildings from nine countries to study energy use in the life cycle of conventional and low-energy buildings. The buildings included residential and non-residential units. In the study, the sum of operating and embodied energy for the total life cycle of the building was calculated and normalized in kWh/m^2 year for each case. In 59 out of 60 cases, the operating energy is greater than the embodied energy; a "self-sufficient solar house" corresponds to the case that includes only embodied energy. The assumed lifetime of the buildings range from 30 to 100 years, and the mode is 50 years.

A conclusion drawn from the case study of 60 buildings is that operating energy dominates all cases. When resource consumption uses embodied energy as a measurement, the highest consumption of resources occurs during the occupancy of the building. This finding leads to the assumption that any reduction in the consumption of resources during the occupancy of the building will have a higher impact on the consumption of resources for the life cycle of the building.

The life cycle of a house and materials are two processes that interact with each other. A holistic approach to the construction life cycle, as represented in Figure 3, results from the combination of these two processes. An interpretation of the construction life cycle is an open system in which there is an exchange between matter and energy with its surroundings.

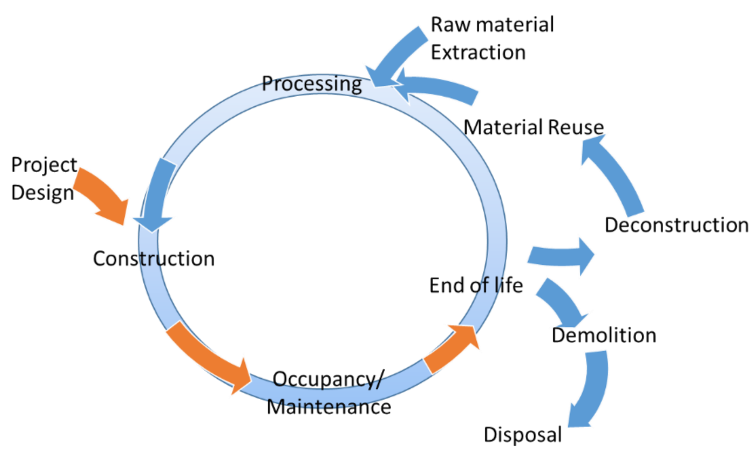


Figure 3. Construction system

2.3 Sustainable development

Sustainable development is a topic that emerges from the concern of policymakers and scholars. The public is also somewhat aware of the importance of sustainable living to preserve resources for future generations. Many points of view about the meaning of sustainable exist due to the constant reference made to the topic and the nonchalant use of the word "sustainable."

In October of 1987, the Brundtland Commission, formally known as the World Commission on Environment and Development (WCED), proposed the first and most acceptable definition of "sustainable development."

> "Sustainable development is a development that meets the needs of the present without compromising the ability of future generations to meet their own needs." (Brundtland et al., 1987)

Sustainable development is a term that initially coined for environmental issues, and it has evolved until becoming a broader term that encompasses economic, environmental, social, and cultural dimensions (United Nations, 2013); these are requisites to maintain living standards of future generations.

2.4 Sustainable construction

In 1994, the First International Conference on Sustainable Construction (SC '94) issued an early definition of sustainable construction. A purpose of the conference was to bring together experts with a common interest in the new discipline called "sustainable construction" or "green construction" (Kibert, 1994). During the conference, the Conseil

International du Batimet pour la Recherche l'Etude et la Documentation (CIB) defined sustainable construction as, "creating and operating a healthy built environment based on resource efficiency and ecological design."

The construction industry uses a variety of terms interchangeably to represent a movement that seeks to include sustainable characteristics in traditional construction. These terms include sustainable construction, sustainable design, green building, green buildings, high-performance building, whole building design, sustainable building, and integrated design (Robichaud & Anantatmula, 2010). Table 1 defines terms that describe environmentally friendly construction practices.

Table 1. Definitions of terms used to describe sustainable practices in construction

Term	**Definition**	**Quoted source**
Sustainable construction	To create and operate a healthy built environment based on resource efficiency and ecological design.	(Kibert, 1994)
Sustainable design	A design philosophy that maximizes the quality of the built environment while minimizing or eliminating negative impacts on the natural environment.	(McLennan, 2004)
Green buildings	Buildings designed, constructed, and operated to boost environmental, economic, health, and productivity performance over conventional buildings.	(US Green Building Council., 2003)
High-performance building	A building with optimized major attributes to ensure long-term operations. These are energy efficiency, durability, life-cycle performance, and occupant productivity.	(National Institute of Building Sciences., 2007)
Net-zero energy Building	A building in which the annual source energy consumption balances with on-site renewable energy, which is possible due to the building's design, construction, renovation, and operation.	(Peterson et al., 2015)

There needs to be a holistic approach to the building life cycle to achieve sustainable practices in the construction industry. Implementation of sustainable principles during the early phases of the building life cycle has a high impact on reaching sustainable goals for the building.

2.5 Standards and rating systems for sustainable housing

Over the last few decades, the construction industry has been incorporating sustainable practices in the construction phase, with most of these practices being motivated by the market rather than by laws or governmental requirements. There are a variety of building assessment methods originated in different countries like BEPAC from Canada, CASBEE, from Japan, CPA from the U.K, and Eco-Quantum from the Netherlands, to mention a few of them (Ding, 2008). In the U.S., for example, certification programs such as the U.S. Green Building Council's Leadership in Energy and Environmental Design (LEED), ENERGY STAR, and EarthCraft program are leading the promotion of sustainable development practices in the residential sector.

ENERGY STAR is a voluntary program promoted by the U.S. Environmental Protection Agency (EPA) that intends to protect the environment and to help businesses and individuals to save money through superior energy efficiency. On the other hand, LEED certification aims to help owners and operators of building to be environmentally responsible and use resources efficiently. LEED is one of the most popular green building certification programs used worldwide. The U.S. Green Building Council (USGBC) developed LEED certification, and it includes a set of rating systems for the design, construction, operation, and maintenance of green buildings, homes, and neighborhoods.

The USGBC certification requires an additional cost and implies a series of stricter requirements concerning material selection, design requirements, and construction process. Home builders are motivated to pursue this type of certification only when it is a requirement of the client or when there is an expectation of an increase in the value of the final product due to the certification by itself.

Since the launch of LEED as a home rating system in 2007, the U.S. Green Building Council reported that in 2014 the number of LEED-certified homes in the world was as high as 150,000 (USGBC, 2014). The number appears to be large, but in contrast to the more than 1,500,000,000 households in the world, LEED certification has only reached 0.01% of the total housing market in the world.

A net-zero-energy building (ZEB) is a residential or commercial building with significantly reduced energy needs due to efficiency gains such that renewable technologies balance energy needs (Torcellini, Pless, Deru, & Crawley, 2006). The U.S. Department of Energy (DOE) and the National Renewable Energy Laboratory (NREL) leads much of the work on net-zero energy buildings. The NREL publication "Zero Energy Buildings: A Critical Look at the Definition" (Torcellini et al., 2006) suggests four definitions for a net-zero-energy building (NZEB), depending on the boundary and metric: Net zero site energy, net-zero source energy, net-zero energy costs, and net-zero energy emissions. Due to the difficulties of fulfilling the requirements of Zero Energy Building, Nearly Zero Energy Buildings (nZEB) is another approach that integrates sustainable practices in construction. Table 2 summarizes the standards and rating systems that are common in the U.S. for the compliance of sustainable construction in the residential sector.

Table 2. Standards and rating systems for sustainable housing

Home Energy Rating System (HERS)	
Type	U.S. Building standard
Building type	Residential
Description	RESNET developed HERS, and it is the nationally recognized system for inspecting and calculating a home's energy performance. A home's HERS Index Score represents a home's energy efficiency. The lower the number, the more energy efficient the home. A home with a HERS Index Score of 0 is a Net Zero Energy Home means that the home produces as much energy through renewable resources, such as solar panels, as it consumes. A home with a HERS Index Score of 70 is 30% more energy efficient than a standard new home. A home with a HERS Index Score of 100 is the same level as a standard new home. This score meets the current industry standard for home energy efficiency. To calculate a home's HERS Index Score, a certified HERS Rater does an energy rating on the home and compares the data against a 'reference home'– the same size and shape as the actual home. The scoring process involves the use of specialized diagnostic equipment.

Table 2. Standards and rating systems for sustainable housing (continued)

	Energy Star
Type	U.S. Building standard
Building type	Homes and commercial facilities (also certify products).
Description	Energy Star is a voluntary program launched by the U.S. Environmental Protection Agency (EPA) and now managed by the EPA and U.S. Department of Energy (DOE) There are two paths to certify a home to earn the ENERGY STAR: The Prescriptive and Performance Paths. Both the Performance and Prescriptive Paths require completion of four inspection checklists: Thermal Enclosure System Rater Checklist HVAC System Quality Installation Rater Checklist HVAC System Quality Installation Contractor Checklist Water Management System Builder Checklist These checklists include building science practices that promote improved comfort, indoor air quality, and durability in certified homes.
	ICC 700 National Green Building Standard (NGBS)
Type	U.S. Building standard
Building type	U.S. single-family and multifamily homes, residential remodeling projects, and site development projects.
Description	The ICC 700 provides independent, third-party verification that a home, apartment building, or land development is designed and built to achieve high performance in six key areas: Site Design, Resource Efficiency, Water Efficiency, Energy Efficiency, Indoor Environmental Quality, and Building Operation & Maintenance. The ICC 700 NGBS contains four levels: Bronze; Silver; Gold; and Emerald. The highest level requires a building to save 60% or more of its energy use. For the NAHB Research Center to grant a higher level

Table 2. Standards and rating systems for sustainable housing (continued)

	of green certification, a home must keep earning higher levels of minimum points in every category. A self-assessment tool is available. However, to receive Certification, an independent "verifier" must conduct the assessment. Verifiers must receive training from the NAHB Research Center's National Green
Living Building Challenge	
Type	International Building standard
Building type	All types of construction, new or existing.
Description	The creators of the Challenge consider it as the "most advanced measure of sustainability in the built environment possible today." Comprised of seven performance areas, or "Petals": Site, Water, Energy, Health, Materials, Equity, and Beauty. Twenty Imperatives subdivide the petals. Each of these focuses on a specific sphere of influence. An independent auditor, such as "Living," certify the building projects. Certified projects must meet all program requirements for 12 consecutive months of continued operations and full occupancy.
Net Zero Energy Buildings	
Type	International Building standard
Building type	All types of buildings.
Description	A Zero Energy Building produces enough renewable energy to meet its yearly energy consumption requirements. The Department of Energy (DOE) for residential and commercial buildings has defined two milestones for NZEB. The priority is to create systems integration solutions that will enable: 1) marketable Net Zero Energy homes by the year 2020 and 2) commercial Net Zero Energy buildings at low incremental cost by the year 2025. There are four ways to define net zero: 1) Net Zero Site Energy, 2) Net Zero Source Energy, 3) Net Zero Energy Costs, and 4) Net Zero Energy

Table 2. Standards and rating systems for sustainable housing (continued)

	Emissions. The International Living Futures Institute's Net Zero Energy Building Certification™ (NZEB) verifies net-zero energy building performance.
Passive House	
Type	International Building standard
Building type	Residential and commercial
Description	The certification criteria of the International Passive House Association (IPHA) includes Space heating demand; space cooling demand; primary energy demand; airtightness and thermal comfort. IPHA: Intelligent design and implementation must include the 5 Passive House principles to fulfill certification requirements. The 5 Passive House principles are thermal bridge free design; superior windows; ventilation with heat recovery; quality insulation; and airtight construction. The certification criteria of the Passive House Institute US (PHIUS) includes air tightness; source energy; and space conditioning. PHIUS: Certification combines a protocol of passive house design verification with a Quality Assurance and Quality Control (QA/QC). Specialized PHIUS+ Raters perform the program on site.
EarthCraft	
Type	Southeastern U.S. Building system with compliance options.
Building type	Homes
Description	EarthCraft is a program of the Greater Atlanta Home Builders Association and Southface. It requires saving energy and water, meeting strict indoor environmental quality standards, and conserving natural resources. The certification focuses on site planning, energy efficiency, water efficiency, resource-efficient design, resource-efficient building

Table 2. Standards and rating systems for sustainable housing (continued)

	materials, indoor air quality, waste management, and homebuyer education. EarthCraft House offers green building certification for single-family detached homes, townhomes, and duplexes. EarthCraft Renovation provides guidelines for renovations or additions to existing homes. Goals include improved indoor air quality and saving energy and water/
Enterprise Green Communities Criteria	
Type	U.S. Building system with compliance options
Building type	Applies to both multifamily and single-family projects
Description	Certified Enterprise Green Communities properties cost less to operate and maintain, they use fewer natural resources, produce less waste, and contain fewer toxic materials, and promote a healthier environment. Technical requirements for Certification include: Integrative Design; Location + Neighborhood Fabric; Site Improvements; Water Conservation; Energy Efficiency; Materials; Healthy Living Environment; and Operations, Maintenance, and Resident Engagement.
Leadership in Energy and Environmental Design® (LEED®)	
Type	International Building system with compliance options
Building type	All building types – commercial, residential, and whole neighborhood communities.
Description	LEED works throughout the building lifecycle. LEED offers a green building certification program that recognizes quality building strategies and practices. To obtain LEED certification, building projects satisfy prerequisites and earn points. Generally, major credit categories include: location and transportation, materials and resources, water efficiency, energy and atmosphere, sustainable sites, indoor environmental quality, innovation credits, and regional priority credits

Finally, lean construction philosophy is another practice recognized as sustainable in the construction industry. It is identified as sustainable because it concerns the alignment and holistic pursuit of concurrent and continuous improvements in all dimensions of the built and natural environment: design, construction, activation, maintenance, salvaging and recycling (Abdelhamid, El-Gafy, & Salem, 2008). Lean construction has its practical development in the processes of design and construction, and it does not intend to improve the use of resources during the operation of the building. The primary motivation for implementing the lean philosophy in a construction project comes from the results in quality improvement and the efficient use of resources during construction, this reduction of "losses" represents economic savings for the builder.

CHAPTER 3 PREVIOUS RESEARCH IN SUSTAINABLE CONSTRUCTION

This chapter presents an overview of prior work in the area of sustainable construction. It summarizes the different approaches towards the integration of sustainable practices in construction. The broad topics that group the efforts are energy, materials, and water.

3.1 Energy

They are two primary goals in the topic of energy: On-site electrical production and reduction of energy consumption. Constructing more energy-efficient buildings can reduce energy consumption. Making buildings energy-efficient results in reducing energy use, energy cost, fossil fuel consumption, and reduction in greenhouse gas emissions. The definition of energy efficiency is using less energy to provide the same service. In the case of buildings, energy efficiency is the result of minimizing the needs of the energy needed for cooling, heating, and lighting. Energy efficiency is achievable through the implementation of different strategies.

One strategy, which is to build passive houses based on the requirements of the Passive House Institute (PHI), is a growing movement in Germany, Austria, and Switzerland. The general criteria of PHI include space heating demand, space cooling demand, primary energy demand, airtightness, and thermal comfort (Passive House Institute, 2016). A case study of 20 passive houses, which took place in Sweden, shows the use of using parametric studies of set points for indoor temperature, solar gains, airtightness, and window types to fulfill criteria (Wall, 2006). The houses are part of a project that includes research, design, construction, monitoring, and evaluation. The project minimizes transmission and ventilation losses, and it uses solar energy for domestic hot water as the strategy to achieve energy efficiency.

A second strategy is the creation of net-zero-energy buildings. The design of Zero Energy Houses can be traced to as early as 1975 when an experimental house, the Zero Energy House, was constructed at the Technical University of Denmark (Esbensen & Korsgaard, 1977). The building structure included high-insulation construction material, heat-recovery equipment, and a solar heating system. For indoor temperature, energy demand, and heat requirements of the house, the designers conducted computational calculations. The design for the one-family, one-storied house includes a solar heating system with a 30 cubic meter insulated storage tank and a 42 square meter solar collector to cover the heat and hot water requirements for the house during a whole year. Although the system suitably met the project goals, it is large for the house dimensions.

Other researchers deal with the integration of renewable sources, like the work of Biaou, Bernier, and Ferron (2006). In that work, the researchers simulated a zero net energy home (ZNEH) in Montreal. The simulations used the software TRNSYS with the interface IISiBat 3. The Home studied was equipped with photovoltaic (PV) panels for on-site electrical production and a geothermal heat pump for space heating and cooling and domestic hot water pre-heating. A case study was also conducted for cold climate in Denver for a three bedroom Zero Energy home (Norton & Christensen, 2007).

In Egypt, the energy simulation tool, ZEBO (Attia et al., 2012), was developed as an informative tool during an early design phase to assist architects with discovering parameters that lead to a zero-energy building and inform them about the sensitivity of each parameter. The tool brings together sensitivity analysis modeling and energy simulation software (EnergyPlus), and it presents a method and a decision-support building simulation. Egyptian residential building components and weather are the bases of ZEBO.

Building performance without considering costs are the bases for the abovementioned studies; studies conducted in Finland cover the resulting research gap (Hamdy, Hasan, & Siren, 2013) and France (Lenoir, Garde, & Wurtz, 2011).

The third type of approach is the inclusion of renewable energy systems (wind turbines, solar collectors, PV and heat pump system, etc.). In Korea, as part of the PLUS 50 project, a design team evaluated the feasibility of new technologies by using a simulation-based decision support system.

A case study involving a multi-family residential building implemented the procedure. In the process involved, the approach used three co-operating programs: EnTrak, which is an energy use information management tool, ESP-r, which is a building simulation software, and Merit, which is a tool that matches supply and demand to make informed decisions about the suitability of specific supply mixes for particular applications (Clarke et al., 2005).

While some authors work on developing tools for automation of the design process while focusing merely on energy efficiency; other authors try to analyze the cost associated with different design options. A high-rise office building in Italy underwent a comparison analysis using six different envelope technologies. The dynamic simulation was used to estimate the energy needs for the building, and then the energy cost was compared with the construction cost to evaluate the economic effects of each building envelope (Becchio, Guglielmino, Fabrizio, & Filippi, 2011). To model the building, the authors used the software Design-Builder, and then it was imported into ESP-r. By using a lifetime of 50 years for the building, the results of this research show that more complex technologies, such as ventilated facades, have a more substantial investment cost that is not compensated by energy savings. Therefore, the solution with the lowest energy consumption is not always the best solution.

The use of computational software as support for the decision-making process that is involved in the design and analysis of energy efficient buildings is widespread. However, predicting the annual energy consumption of a house or examining the energy impact of design alternatives requires a different modeling approach than, for example, predicting the peak electrical demand in cooling dominated building (Purdy & Beausoleil-Morrison, 2001). Notably, a software user mandatorily makes numerous assumptions when creating a model, and each assumption and decision affects simulation predictions. Consequently, the study of significant factors in modeling buildings is a topic of interest for some authors.

A study in Finland presents a multi-objective optimization approach based on a genetic algorithm combined with IDA ICE, which is a building performance simulation program. The combination is used to minimize the carbon dioxide equivalent emissions and investment cost for a two-story house and its HVAC system. The design variables taken into consideration were a heating/cooling energy source, heat recovery type, and six building envelope parameters (Hamdy, Hasan, & Siren, 2011). Also, in Finland, a seven-step procedure was developed to determine the optimal cost and nearly zero energy building (nZEB) performance levels. In this study, four construction concepts underwent simulations and cost calculations. The procedure includes the specification of building-envelope components based on specific heat loss coefficients and systems calculation with post-processing of energy simulation results (Kurnitski et al., 2011). Turkey (Ganiç & Yılmaz, 2014) and Italy (Becchio et al., 2011) performed a similar study.

Later studies have included the analysis of life-cycle cost along with the inclusion of sustainable strategies. Bolling and Mathias (2008) compared four heating and cooling systems, which implemented solar thermal energy and non-renewable backup energy, for the same residential house located in five different cities in the United States. The study included the development of a comprehensive program that predicts the entire life cycle cost, energy usage, energetic efficiency, and energy destruction.

3.2 Materials

Attempts aimed at separating separate energy-efficiency from the selection of materials have been difficult. A large number of studies that relate to the selection of energy-saving building components use computational tools to support their work. As new tools emerge, some researchers work on the integration of tools to optimize the process of selecting components. The work of de Wilde and Van Der Voorden (2004) deals with the problem of integrating building simulation tools and building design. The problem was initially narrowed down to computational support for one specific type of building design decision: the selection and integration of one or more energy-saving building components such as solar walls, advanced glazing systems, and sunspaces into a given building design.

The work of de Wilde continues with the Design Analysis Integration (DAI) initiative (Augenbroe et al., 2004). The study deals with the integration of building performance analysis tools and the building design process, and it proposes new solutions for design analysis integration while addressing problems in the ongoing efforts towards tool interoperability. The result is a prototyping workbench that integrates four layers: design information, structured simulation models, analysis scenarios, and software application and tools with an emphasis in the last two layers, which is a strategy that focuses on creating collaborative environments.

Another example of the achievement of energy efficiency through the integration of computational tools for the simulation and design of a detached house took place in Sydney, Australia (Bambrook, Sproul, & Jacob, 2011). The building energy simulation program, IDA Indoor Climate and Energy 4.0, was coupled with the optimization program, GenOpt 2.0, to analyze the space heating and cooling requirement of a simple house. The simple building was optimized concerning life-cycle cost to improve the building energy performance. The process included passive solar design, a comprehensive level of insulation for the building envelope, thermal mass, high-performance windows, minimized losses due to ventilation and air infiltration, and optimized shading and glazing areas depending on orientation.

To minimize the energy consumption of Mediterranean buildings, Znouda, Ghrab-Morcos, and Hadj-Alouane (2007) used an optimization algorithm that couples pseudorandom optimization techniques, the genetic algorithms (GA), with a simplified tool for building thermal evaluation (CHEOPS). Because increasing energy performance usually requires using individual devices with high construction costs, the authors also propose to use GA for economic optimization. Genetic algorithms were coupled with a dynamic thermal model to find the appropriate trade-offs in the Mediterranean context of Tunisia (Znouda et al., 2007). The financial cost included the construction investments, purchase price, and maintenance cost of the heating and air-conditioning systems, as well as the cost of the total energy consumption throughout the life cycle of the building.

Other works, such as the work in the United Kingdom by Wang, Gwilliam, and Jones (2009), have studied the selection of building materials and openings. They conducted a parametric study of the design of a zero-energy house to simulate a residential house in the United Kingdom using the simulation software EnergyPlus. Their simulation took into consideration building materials, window sizes, window orientations, and TRNSYS to investigate the feasibility of zero energy house with renewable electricity, solar hot water system, and energy efficient heating systems. The study concluded that it is theoretically possible to have zero-energy homes in the UK.

Ferrara et al. (2014) performed a simulation-based optimization study of cost-optimal analysis for nearly Zero Energy Building in France. The method combines the use of TRNSYS, which is a dynamic energy simulation software, with GenOpt, which is Generic Optimization program. The result is a definition of a cost-optimal set of design parameters for different types of envelope system/technical system combinations. The goal of the study was to find the cost-optimal level for the French single-family building typology.

Hasan, Vuolle, and Sirén (2008) combined simulation and optimization to minimize the life-cycle cost (LCC) for a single-family detached house in Finland. The approach used the building performance simulation program IDA ICE 3.0 with the GenOpt 2.0 generic optimization program to find optimized values of five design variables for the construction of the building construction and HVAC system. The study used the variables of insulation thickness for the external wall, roof, and floor (continuous variables), as well as the type of heat recovery and U-value of the windows (discrete variables). Another study optimized the cost with a building energy simulator to reduce annual requirements of heating and cooling to the point of making climate control system unnecessary. The optimization used a net present cost analysis, including the construction cost, the HVAC capital cost, and the electricity cost for space heating and cooling. The insulation thickness of walls and roof, window type, the thickness of an internal thermal mass wall, and air exchange rate for night ventilation were varied during the optimization (Bambrook et al., 2011).

3.3 Water

Developed countries and regions implement water conservation practices to achieve sustainable water demand management. Location, function, and personal preferences influence water demand (Lee et al., 2011). Furthermore, some characteristics of properties like different size (number of bedrooms), architectural type (e.g., flats vs.

terraced), and garden presence could influence household water demand (Fox, McIntosh, & Jeffrey, 2009).

Residential water conservation practices include the use of efficient water appliances such as showers, toilets, and clothes washers in residential units. The following aspects make residential water conservation effective: (1) residential customers account for the majority of water demand in urban areas, (2) residential appliances, such as showers, toilets, and washing machines, constitute the majority of household water demand, and (3) the potential water savings through water efficient appliances are well acknowledged (Balbin et al., 2010, Baumann et al., 1998, Fidar et al., 2010, Kenney et al., 2008, Lee et al., 2011, Millock and Nauges, 2010 and Olmstead and Stavins, 2009). Also, the public sympathizes more with incentives to switch to water-efficient units (i.e., rebates or unit exchange programs) than with other water management policies such as price increase or water restrictions (Millock and Nauges, 2010 and Randolph and Troy, 2008).

Rainwater harvesting and reuse of greywater is a way to promote potable water savings in buildings (Ghisi & Ferreira, 2007). A rainwater collection system in residential areas can be used to supply supplement drinking water (Villarreal & Dixon, 2005), for flushing toilets with rainwater collected from roofs (Fewkes, 1999), and for general use to save potable water (March, Gual, & Orozco, 2004). Studies have also taken place regarding the reuse of greywater as an option for reducing potable water for flushing toilets, groundwater recharge, landscaping, and plant growth (Christova-Boal, Eden, & McFarlane, 1996; March et al., 2004, Al-Jayyousi, 2003). Others have explored the possibility of using combinations of rainwater collection and greywater reuse (Dixon, Butler, & Fewkes, 1999).

3.4 Conclusions

This chapter presents an overview of the previous research in sustainable construction. The research is grouped in this chapter in three topics: energy, materials, and water. There is a body of knowledge that addresses the consequences of selecting sustainable parameter in construction. This consequences are determined in terms of energy use, water use, and cost of materials, but does not include a plan for the selection of parameters in the early stages of design of single-family housing.

The review shows the strategies and approaches studied by experts in the area. Different computational tools have been created for each type of specialty, but often the interfaces do not allow to import information from one tool to another. Consequently, the project has to be modeled again in each software, a great amount of work and coordination with experts is implied.

CHAPTER 4 INTEGRATION OF SUSTAINABLE PARAMETERS IN HOUSING PROJECT DELIVERY

4.1 Impact of buildings in resource consumption

The U.S. Energy Information Administration (EIA, 2018) estimates that the residential and commercial sector used about 40% of total U.S. energy consumption in 2017, approximately 39 quadrillion British thermal units (BTUs). The residential sector was responsible for 20.9% of the total 2017 energy consumption. Furthermore, the residential sector only represented 17.51% of the total energy share in 1949, which implies that the residential sector has increased its consumption at a higher rate in comparison to other sectors, particularly the industrial sector. Figure 4 shows the decrease in the industrial sector energy consumption over the past sixty years. Part of the decline in energy consumption is due to the outsourcing of American manufacturing; in 1965, manufacturing accounted for 53% of the economy in contrast to 9% in 2004 (Morley, 2006).

Trend changes in the lifestyle of the US population, such as the increase in the number of home-based businesses and the number of work-from-home jobs, further influence overall energy consumption. The fact that the residential sector consumes twenty percent of the nation’s total energy consumption justifies the importance of sustainable practices for residential buildings.

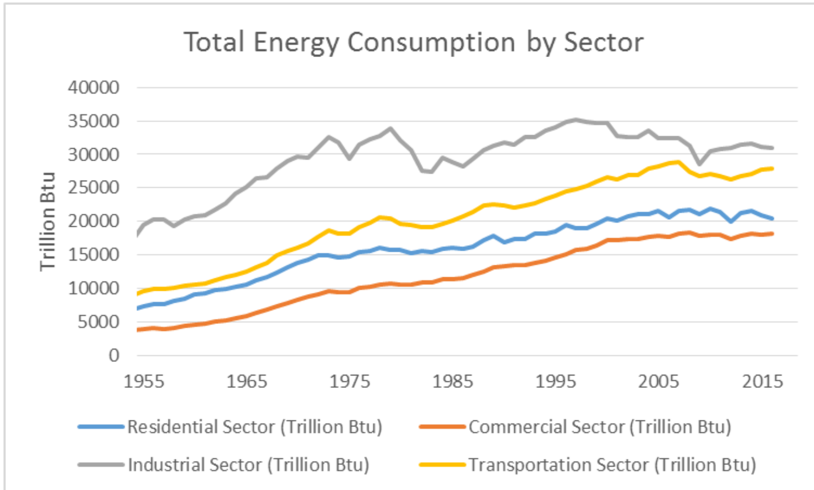


Figure 4. Total energy consumption by sector 1955-2015.

Note: Data from the U.S. Energy Information Administration, 2018

The following three main groups summarize the energy requirements of the residential sector: electricity, fossil fuels, and renewable energy. Electricity corresponds to 70% of the total residential energy demand when energy losses of the electrical system. Energy losses of the electrical system due to conversion, transmission, and distribution of energy from power plants to end-use consumers correspond to 66.5% of the energy consumed by the electrical system (Figure 5). These losses are the difference between the energy consumption of the electric power sector and the energy content of retail electricity sales.

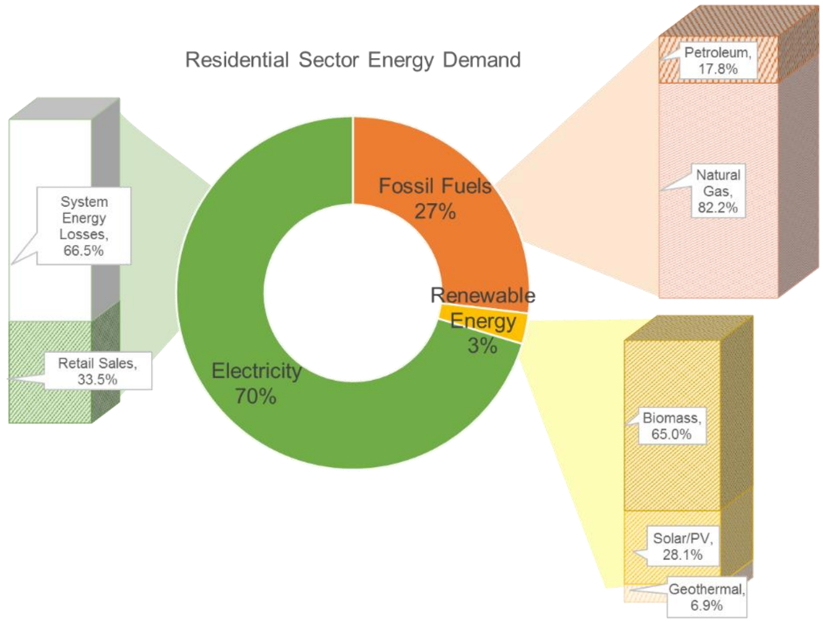


Figure 5. Distribution of residential sector energy demand for 2017.

Note: Data from the U.S. Energy Information Administration, 2018

In 2017, the on-site energy consumption of the residential sector in the United States was 10,847 Trillion Btu. The electrical consumption from the grid and fossil fuels account for 95% of the energy consumed by this sector (Figure 6); the remaining 5% corresponds to renewable energy sources (e.g., biomass, solar/PV, geothermal).

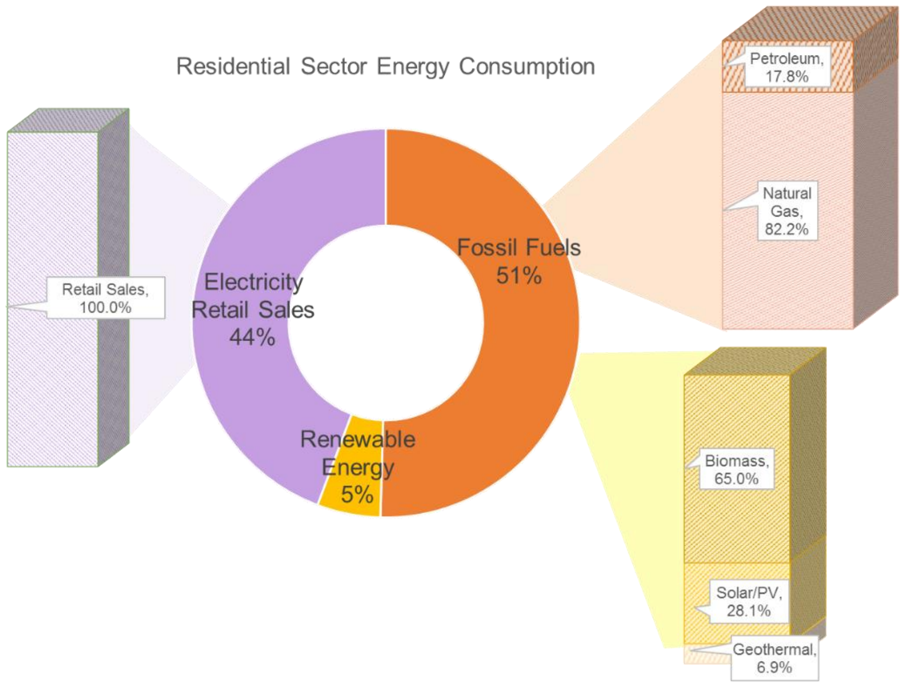


Figure 6. Distribution of residential sector energy consumption for 2017.

Note: Data from the U.S. Energy Information Administration, 2018

For a typical building, most resource consumption occurs during occupancy and maintenance of the building, which also applies to residential buildings with an assumed lifetime greater than 30 years. Hence, reducing energy consumption during the occupancy and maintenance phase will have the highest impact on the total consumption of resources associated with the building. The preceding justifies the tendency of the industry and academia to work towards designing and constructing energy efficient buildings.

Figure 7 shows the life cycle of a single-family house. As seen in the figure, the longest stage in the life cycle is the occupancy stage. Nevertheless, decision makers in the residential sector focus on resource consumption during construction, especially in single-family projects. Consequently, selling sustainable houses is not a motivation for residential builders.

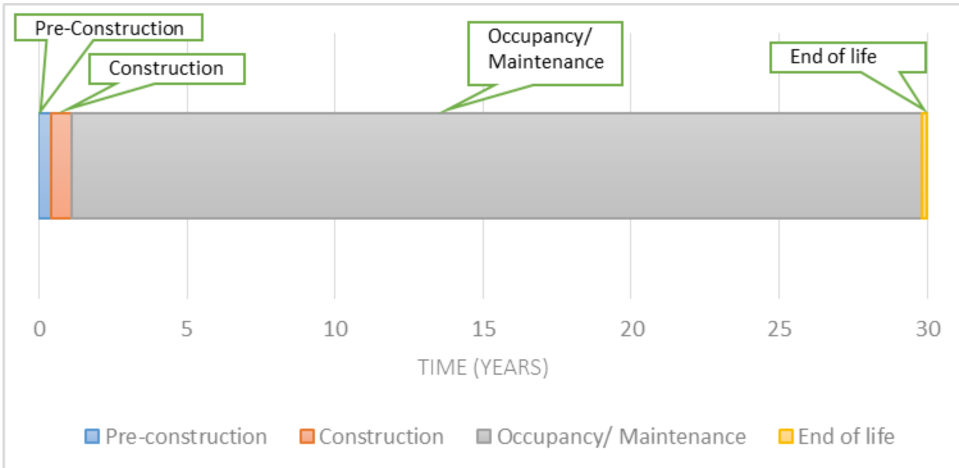


Figure 7. The life cycle of a typical single-family house.

The majority of decisions concerning the type, quantity, and quality of materials occur during the project's pre-construction phase. During the pre-construction phase, the resource consumption for the building is nearly zero. However, the pre-construction phase has a high impact on decisions that lead to resource usage during the construction and occupancy phases. The findings of a case study conducted in the Netherlands for the building design process of building projects show that selection of the energy-saving building components mostly takes place during the conceptual design, and the selection of 71% of those components do not have computational support (de Wilde & Van Der Voorden, 2004). The same study also points out that energy-saving building components are selected based on previous experiences with the components in prior projects. Furthermore, the study species that the selection of 80% of the components takes place without alternative considerations.

The construction phase has the highest rate of material consumption. During this phase, one of the earliest affected resources is the land. Any residential project requires land, and eliminating this resource from a residential construction is nearly impossible. Notwithstanding, reducing the footprint of the constructed house moderates land consumption. The construction process also has a high impact on the environment. In effect, this activity has an impact on the construction site and its surroundings, the environment of the material extraction and processing sites, and the environment of waste disposal generated during the construction process.

The construction time of a residential house varies depending on several factors such as the project size, the experience of the contractors, location, and weather. An average residence often takes between seven to eleven months to build (NAHB, 2015). Disregarding any renovation that a house might undergo after its initial erection, construction consumes over 90% of the materials used by a house during its lifespan. The remaining 10% of the materials get used during the 30 to 50 years of occupancy.

The greatest resource consumption takes place during building occupancy and maintenance phase. This process consumes the most water and energy than any other process during the building lifecycle. In most cases, as shown in section 5, the operating energy requirements during building occupancy is higher than the embodied energy used during construction. For example, Sartori and Hestnes (2007) present a case of a single residential home located in the United States (case number 35). The calculated total embodied energy for that residential home is 25 kWh/m^2y, and the operating energy is 230 kWh/m^2y. Thus, in this case, the operating energy nine folds the embodied energy required for construction. The final user might not easily perceive the impact of the operating energy during the occupancy and maintenance phase due to the different rate of resource consumption during these two phases. For example, assuming seven months of construction and a 30-year lifespan for a residential home, construction consumes almost 107 kWh/m^2 per month. In contrast, energy consumption during occupancy is 19.6 kWh/m^2 per month. This perception becomes a decisive factor of end users when considering the savings associated with a sustainable house compared to a traditional one.

Finally, the end-of-life phase consumes energy, and it affects the environment due to the waste disposal generated during demolition. Material recycling mitigates environmental impact, but unfortunately, not all materials are reusable.

4.2 Housing project delivery

A simplified representation of project delivery is a process that includes the two main phases; that is, the pre-construction phase and the construction phase. The milestone or deliverable achievements characterize the subdivision of the phases. Figure 8 shows a typical scheme of project delivery for a single-family house. Interrelated stages divide the phases; likewise, the decisions made in each stage affect subsequent stages.

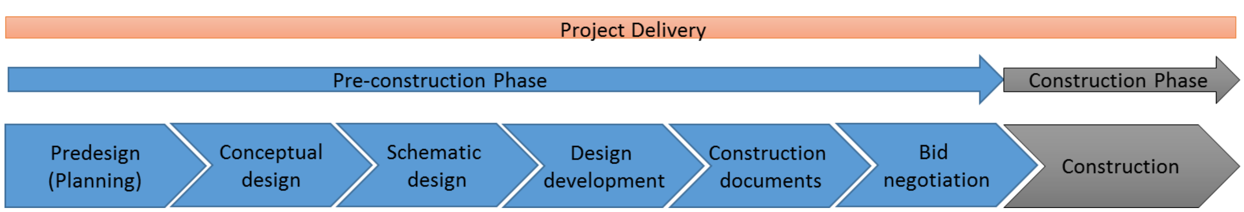


Figure 8. The sequence of project delivery phases for housing projects

4.2.1 Predesign.

House programming occurs during the predesign stage. An outcome of this stage is an outline of user goals and needs. Architectural style, space adjacencies, residence type, and project budget are factors defined in this stage; this stage excludes the drafting of drawings. For this document, the predesign stage is part of the pre-construction phase.

4.2.2 Conceptual design.

Conceptual design implements result from the predesign to create a project vision. Conceptual sketches and models that communicate ideas to the client result from this stage. A highly detailed model is unnecessary at this point. Usually, the design team will generate two, three, or more models to ensure that the envisioned conceptual design meets client expectations.

4.2.3 Schematic design.

Conceptual design results become architectural drawings during the schematic design. Deliverables at the end of this stage are buildings plans, elevations, sections, and site plans. Planning commissions use the schematic design to ensure compliance with zoning, planning, and city requirements. The design of the building is nearly complete at the end of this stage.

4.2.4 Design development.

Schematic design refinement occurs during design development. The design development stage is when details about wall sections, interior elevations, preliminary schedules for finishes, and materials become defined.

4.2.5 Construction documents.

The last stage of the pre-construction phase is drafting construction documents. Designs get finalized, and drawings evolve into rigorous technical drawings during this last stage. Structural, civil, mechanical, electrical, and plumbing drawings are generated per architectural drawings and coordination of each specialist. Then, construction documents are used to obtain permits and requirements for bidding and execution of construction services.

4.2.6 Construction.

The design finally materializes in the construction phase. As the project advances, changes during the construction phase become increasingly limited, and the cost to implement any change also increase as the project progresses during the construction phase. Figure 11 is a summarized representation of the project delivery phases for a house.

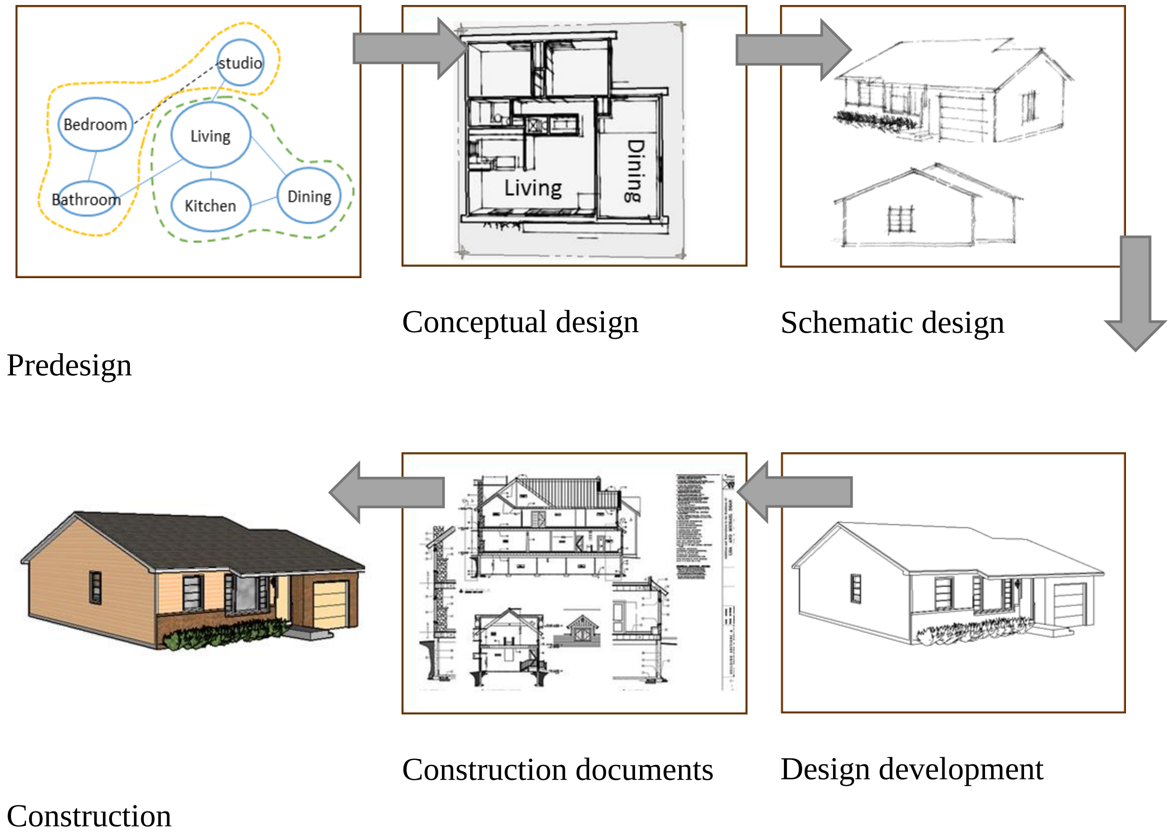


Figure 9. Representation of the pre-construction phase for housing projects

4.3 Sustainable parameters in construction

CHAPTER 3 includes a review of previous research in sustainable construction to identify the sustainable parameters studied by previous authors. The publications were classified into five different groups according to the main design criteria in each research: energy-efficient, zero-energy buildings, renewable energy systems, nearly zero energy buildings, and minimization of life cycle cost. Also, a list of specific parameters was created and later grouped into nine design and analysis parameters. Table 3 identifies the design and analysis parameters studied by each author. The resulting matrix contains the design criteria and the design and analysis parameters.

Table 3. Literature review of design and analysis parameters

uthor	Location	Orientation	Building form/geometry	Building envelope	Arrangement/ Grouping of spaces	Space Conditioning	Energy efficiency	Water Efficiency	Renewable Energy	life cycle Cost
Design criteria: Energy-efficient										
(Wall, 2006)				✓		✓	✓			
(de Wilde & Van Der Voorden, 2004)	✓	✓	✓	✓	✓	✓	✓			
(Bolling & Mathias, 2008)	✓	✓	✓	✓		✓	✓		✓	✓
(Bambrook et al., 2011)	✓	✓	✓	✓			✓			✓
(Znouda et al., 2007)	✓	✓	✓	✓						✓
(Becchio et al., 2011)	✓	✓	✓	✓	✓	✓	✓			✓
(Purdy & Beausoleil-Morrison, 2001)			✓	✓						

Table 3. Literature review of design and analysis parameters (continued)

Author	Location	Orientation	Building form/geometry	Building envelope	Arrangement/ Grouping of spaces	Space Conditioning	Energy efficiency	Water Efficiency	Renewable Energy	life cycle Cost
(Gossard, Lartigue, & Thellier, 2013)	✓	✓	✓	✓	✓	✓	✓			
Design criteria: Zero-energy buildings										
(Attia et al., 2012)	✓	✓	✓	✓		✓	✓		✓	
(Wang et al., 2009)	✓	✓	✓	✓	✓	✓	✓		✓	
(Biaou et al., 2006)	✓	✓	✓	✓	✓		✓		✓	
(Lenoir et al., 2011)	✓			✓		✓	✓		✓	
(Norton & Christensen, 2007)	✓	✓	✓	✓		✓	✓		✓	✓
Design criteria: Renewable energy systems										
(Clarke et al., 2005)	✓	✓	✓	✓	✓	✓	✓		✓	
Design criteria: Nearly zero energy buildings										
(Ferrara et al., 2014)	✓	✓	✓	✓	✓	✓	✓			✓
(Kurnitski et al., 2011)	✓	✓	✓	✓	✓	✓	✓		✓	✓
(Hamdy et al., 2011, 2013)	✓	✓	✓	✓	✓	✓	✓		✓	✓
Design criteria: Minimization of life cycle cost										
(Hasan et al., 2008)	✓		✓	✓		✓	✓			✓
(Hamdy et al., 2011, 2013)	✓	✓	✓	✓	✓	✓	✓			✓
(Ganiç & Yılmaz, 2014)	✓	✓	✓	✓	✓	✓	✓			✓
(Hamdy et al., 2011, 2013)	✓	✓	✓	✓	✓	✓	✓		✓	✓

Each one of the nine design and analysis parameters contains a selection of specific parameters. For example, Table 4 presents a list of specific parameters that are part of the building envelope.

Table 4. Specific parameters for building envelope

Specific parameters	Design and Analysis Parameter (Grouped Parameter)
Window to Wall Ratio (WWR)	
Shading	
Solar Heat Gain Coefficient SHGC	
Insulation U-value	
Insulation thickness	Building envelope
Ceiling U-Value	
Glazing systems	
Wall U-value	
Windows U-value	

On the other end, Figure 10 shows the design and analysis parameters studied by different authors. From the figure, the most frequently found parameter in referenced studies is building envelope.

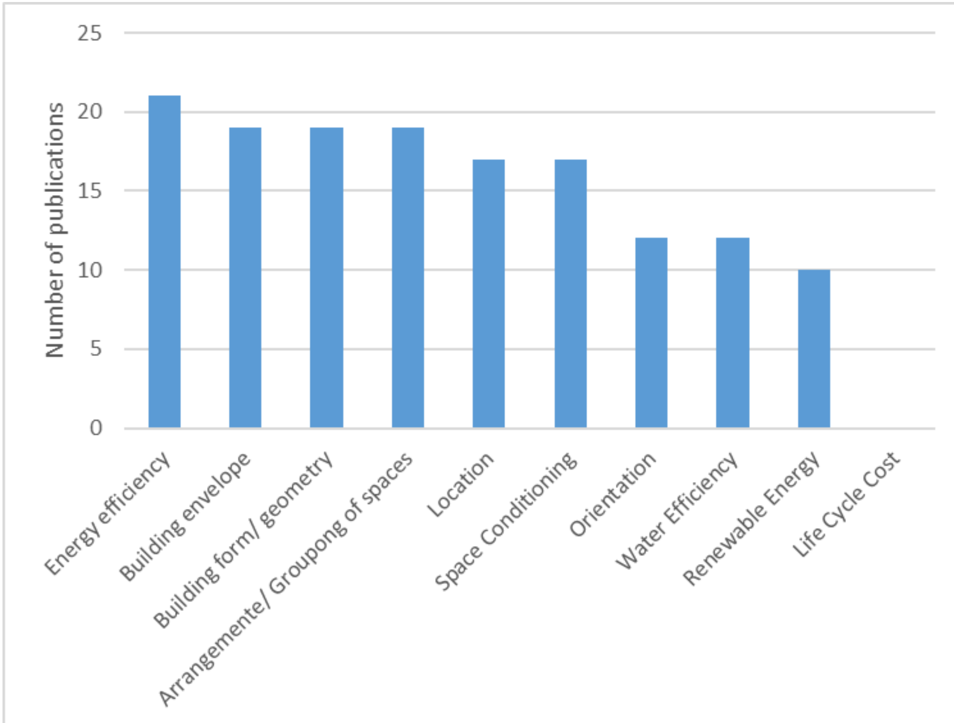


Figure 10. Design and analysis parameters studied by different authors.

The research community has targeted their research towards the reduction of energy consumption and the integration of renewable energy components in the construction of buildings. There is no significant research in the areas of water efficiency and integration of food in residential housing. Lastly, there are no findings of studies describing the selection of sustainable construction components in local housing projects.

Figure 11 shows the nine design and analysis parameters identified in the literature. The parameters are location, orientation, building form/geometry, building envelope, arrangement and grouping of spaces, space conditioning, energy efficiency, water efficiency, and renewable energy.

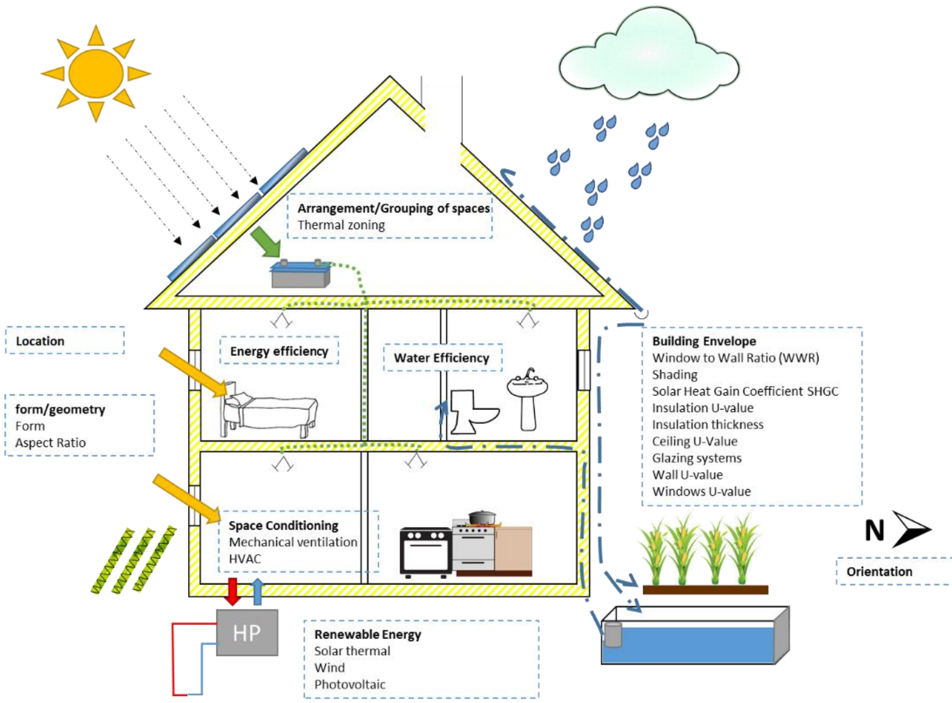


Figure 11. Representation of the design and analysis parameters

All of the design parameters affect the selection of construction components for a house. A matrix chart was created using the Uniformat System for the construction components and the design and analysis parameters identified from referenced studies in sustainable construction. The matrix chart in Table 5 shows the effect of each design and analysis parameter on construction components.

Table 5. Construction components affected by design and analysis parameters

Construction component	Location	Orientation	Building form/ geometry	Building envelope	Arrangement/ grouping of spaces	Space conditioning	Energy efficiency	Water efficiency	Renewable energy	Life cycle cost
A1030 - slab on grade	X		X							X
A2020 - basement walls	X	X	X	X			X		X	X
B1010 - floor construction	X	X	X	X			X		X	X
B1020 - roof construction	X	X	X	X			X		X	X
B2010 - exterior walls	X	X	X	X			X		X	X
B2020 - exterior windows	X	X	X	X			X		X	X
B2030 -exterior doors	X	X	X	X						X
B3010 - roof covering	X	X	X	X			X		X	X
B3020 - roof openings	X	X	X	X			X		X	X
C1010 - partitions			X		X	X	X		X	X
D2010 - plumbing fixtures								X		X
D2020 - domestic water distribution								X		X
D2030 - sanitary waste								X		X
D2040 - rainwater drainage								X		X
D2090 - special plumbing systems								X		X
D3010 - energy supply	X						X		X	X
D3020 - heat generating systems	X				X	X	X		X	X
D3030 - refrigeration	X				X	X	X		X	X
D3040 - HVAC distribution systems					X	X	X		X	X
D3050 - terminal & package units						X	X		X	X
D3060 - HVAC controls & instrumentation						X	X		X	X
D3090 - other special HVAC sys. & equip.	X					X	X		X	X

Table 5. Construction components affected by design and analysis parameters (continued)

Construction component	Location	Orientation	Building form/ geometry	Building envelope	Arrangement/ grouping of spaces	Space conditioning	Energy efficiency	Water efficiency	Renewable energy	Life cycle cost
D5010 - electrical service & distribution	X					X	X		X	X
D5020 - lighting & branch wiring					X	X	X		X	X
D5090 - other electrical systems	X						X		X	X
G3010 - water supply & distribution system.								X		X
G3020 - sanitary sewer systems								X		X
G3030 - storm sewer systems								X		X
G3040 - heating distribution	X				X	X	X		X	X
G3050 - cooling distribution	X				X	X	X		X	X
G3060 - fuel distribution							X		X	X
G3090 - other civil/mechanical utilities							X		X	X
G4010 - electrical distribution							X		X	X

The design and analysis of buildings use specific parameters based on a literature review. Subsequent relationships with the construction components also use these parameters. Notwithstanding, there needs to be an additional study that includes local builders to compare these findings with current practices in the homebuilding industry.

4.4 Integration of sustainable parameters in construction

The literature review shows two important findings that have a direct impact on current sustainable practices in construction. The first finding is the perception that energy efficiency is the most accepted sustainable building practice, and the second finding is that the selection of the majority of sustainable parameters takes place during the early stages of the pre-construction phase.

A case study conducted in the metropolitan area of Rochester, New York supports the first finding. A survey was conducted to homebuilders, focusing on four primary categories: market perceptions, information gaps, infrastructure issues, and implementation issues (Tomkiewicz, 2011). The study identified a lack of understanding of sustainable development practices as the largest barrier to sustainable residential development. The results from this study show that 87% of building professionals do not believe residential housing hurts the environment. Nevertheless, this lack of clarity related to the true meaning of sustainable development, energy efficiency is the most accepted and seemingly understood of all sustainable building practices. Furthermore, 89.7% of respondents exhibited high levels of confidence in their abilities to apply energy efficient standards to their residential construction projects.

A second finding, supported by the analysis of energy-efficient building design projects conducted by de Wilde and Van Der Voorden (2004), is that during conceptual design most of the energy-saving building components are selected and that the selection of these components takes place based on the use of the components in earlier projects. Another relevant finding of the above case study is the use of building simulation tools after the completion of the conceptual design phase. The tools are used to verify expectations about energy consumption or to optimize the selected components, rather than for support to select energy-saving building components from a range of options.

4.5 Barriers to integrating sustainable practices in the homebuilding industry

The concerns and barriers identified in the literature fall into four primary groups similar to the ones proposed by Meryman and Silman (2004) in New York, and Qi, Shen, Zeng, and Ochoa J (2010) in China.

The work by Meryman and Silman (2004) identifies three barriers groups that practitioners encounter when they attempt to use sustainable practices in engineering, economic, policy, and technical issues. These barriers have been used to classify potential barriers in the implementation of green practices in the construction industry (Lam, Chan, Chau, Poon, & Chun, 2009). Furthermore, these have been expanded to the following four primary barriers in the implementation of green construction in China: economics, technology, awareness, and management (Shi, Zuo, Huang, Huang, & Pullen, 2013); Table 6 lists the barriers.

Table 6. Typical barriers to implementing sustainable construction in housing projects.

Adapted from (Shi et al., 2013)

Barriers	**Key references**
Economics	
Cost	
Additional costs due to appliance choice and energy-saving materials	(Tomkiewicz, 2011), (Zhang, Shen, Wu, & Qi, 2011), (India Habitat Centre., 2006), (Wilson & Tagaza, 2006), (Yudelson, 2008), (de Wilde & Van Der Voorden, 2004), (Purdy & Beausoleil-Morrison, 2001), (Attia et al., 2012), (Augenbroe et al., 2004)
Higher cost in relation to customers demand	(Ferrara et al., 2014), (Wilson & Tagaza, 2006),
Unequal distribution of benefits	(Yudelson, 2008), (Hwang & Tan, 2012), (Wilson & Tagaza, 2006)
Time	
Incremental time caused by unfamiliarity with sustainable technologies	(Attia et al., 2012), (Augenbroe et al., 2004), (Purdy & Beausoleil-Morrison, 2001)
The lengthy approval process for new technologies and recycled materials	(Yudelson, 2008), (Hwang & Tan, 2012), (Wilson & Tagaza, 2006)
Technology	
Reduction of structure aesthetic	(Shi et al., 2013)
Uncertainty in the performance of green materials and equipment	(Shi et al., 2013)
Imperfect green technological specifications	(Shi et al., 2013)
Misunderstanding of green technological operations	(Shi et al., 2013)

Table 6. Typical barriers to implementing sustainable construction in housing projects (continued)

Barriers	Key references
Restrictions on new green production and technology	(de Wilde & Van Der Voorden, 2004), (Attia et al., 2012), (Purdy & Beausoleil-Morrison, 2001).
Awareness	
Lack of information and knowledge	(Zhang et al., 2011), (India Habitat Centre., 2006), (Williams & Dair, 2007)
Sustainable measure not required by the client	(Williams & Dair, 2007), (Tomkiewicz, 2011)
Dependence on promotion by government	(Williams & Dair, 2007), (Zhang et al., 2011)
Insufficient policy implementation efforts	(Hwang & Tan, 2012), (Williams & Dair, 2007), (India Habitat Centre., 2006)
Management	
Lack of support from senior management	(Shi et al., 2013), (Wilson & Tagaza, 2006)
Lack of knowledge of green technology and materials	(Wilson & Tagaza, 2006), (Hwang & Tan, 2012)
Limited availability of green suppliers and information	(Wilson & Tagaza, 2006),
Lack of quantitative evaluation tools for green performance	(Augenbroe et al., 2004), (Hwang & Tan, 2012)
Technical difficulty during the construction process	(Wilson & Tagaza, 2006)

4.5.1 Economics.

4.5.1.1 Cost.

While the expected economic benefit from savings in energy and water can be used to promote the acquisition of sustainable houses (Tomkiewicz, 2011), the economic factor has been recognized as a critical barrier to the implementation of green initiatives strategy in the real estate development process (Zhang et al., 2011). Several studies suggest that there is a perception of increased financial risk including higher initial capital costs (India Habitat Centre., 2006), financial modeling biased towards short-term paybacks rather than life cycle costing (Wilson & Tagaza, 2006), and higher cost to construct green buildings as compared with conventional buildings (Yudelson, 2008). In addition to those general perceptions, the lack of data on life-cycle costs of the application of sustainable initiatives often deters usage of resource efficiency measures (India Habitat Centre., 2006). Materials and design, customer demand, and distribution of benefits are the main causes of these economic barriers.

Sustainable materials and appliances have additional attributes that, in some cases, make them costlier when compared to traditional ones. The cost of materials becomes a barrier when this situation affects the overall project cost and the expected profit margins of the developer. In some cases, the developer decides to change the materials specified during construction because of unacceptably high costs or availability and timely supply issues (Wilson & Tagaza, 2006). On other occasions, companies decide not to use green strategies at the final stage to avoid incurring in higher costs, and it was rather difficult to purchase the green materials and appliances for the property (Zhang et al., 2011).

In addition to the cost of materials and appliances, sustainable practices also affect costs during pre-construction. Costs increase due to additional experts, the need for sophisticated tools (de Wilde & Van Der Voorden, 2004), additional time for data gathering and inputting (Purdy & Beausoleil-Morrison, 2001), and the integration of design aspects during the early phases of the project (Attia et al., 2012; Augenbroe et al., 2004). Other factors leading to the high-cost premium of green buildings is the cost incurred in the search for green alternatives and certification of buildings (Yudelson, 2008).

A second cost barrier is customer demand that is associated with the sale of sustainable housing. Ferrara et al. (2014) sustain that the design of nearly zero energy buildings is not yet profitable in terms of costs. Concerning tenant occupied buildings, Wilson and Tagaza (2006) affirm that there is a lack of tenant demand for green buildings.

The last barrier found by researchers is the unequal distribution of benefits. It is difficult to convince the developer to build sustainable projects when there is an unequal distribution of advantages amongst the builder and tenants (Yudelson, 2008). Developers perceive that they have to fork out the high-cost premium for green buildings while the tenants accrue most of the benefits generated from the green building, such as better indoor environment quality and cost savings in energy and water (Hwang & Tan, 2012). In other words, there are split incentives amongst the developers, owners, and tenants with the developers reluctant to increase capital costs for a building that currently generates similar rental returns for the owners while the long-term operational savings are passed directly to the tenants (Wilson & Tagaza, 2006).

4.5.1.2 Time.

As mentioned above, additional time is required to perform simulations and to gather data for sustainable design (Attia et al., 2012; Augenbroe et al., 2004; Purdy & Beausoleil-Morrison, 2001). In general, more time is needed at the pre-construction phase to fully integrate design features which the form of the selected project contract must reflect (Wilson & Tagaza, 2006). Furthermore, the market environment suggests that the planning process can protract because the approval process to use new green technologies and recycled materials can be lengthy (Wilson & Tagaza, 2006). A lengthy approval process presents a challenge to project managers because they must develop the schedule and approve progress payments to vendors and suppliers (Hwang & Tan, 2012). During construction, random checks and on-site visits by project managers are usually mandatory to ensure that sustainable practices are implemented on-site (Wilson & Tagaza, 2006), which is essential because workers tend to forego time-consuming sustainable practices when there are tight project deadlines (Hwang & Tan, 2012).

4.5.2 Technology.

Green materials and equipment are crucial elements of sustainable construction. The use of these elements sometimes cause trouble for designers and affect the aesthetic appearance of a building (Shi et al., 2013). The degradation of aesthetic appearance derived from the adoption of sustainable technologies is a concern for stakeholders. For example, the use of curtain walls and the installation of solar panels usually force architects to spend time addressing the issue of the solar panel integration with the façade or the roof.

The development of new building-energy-simulation tools shows a continuous increase in capabilities and complexity. This trend seems to expand the barriers to integrate building design and building simulation even further since a high level of expertise is needed to fully utilize simulation tools (de Wilde & Van Der Voorden, 2004). Some authors affirm that the integration of design aspects during the early design phase is extremely complex, and it requires a high level of expertise (Attia et al., 2012). The authors affirm that a solid grounding in the principles of building physics and considerable experience in the application of simulation is necessary when a tool presents the user with so many degrees of freedom (Purdy & Beausoleil-Morrison, 2001).

Some authors identify the interoperability among design tools as another barrier. When working with computer tools created for analyzing and designing sustainable features, the collaboration between architects and energy systems specialist is particularly weak (Yun et al., 2003: cited in Clarke et al., 2005) due to problems related to data exchange between design and simulation (Augenbroe et al., 2004). A large number of analysis tools are available, but there is a need to enable more effective and efficient use of existing and emerging building performance analysis tools by collaborating building engineering team. Correspondingly, design can be more complicated than that of a conventional building due to the evaluation of alternative materials and systems (Hwang & Tan, 2012). Likewise, some of the main challenges in sustainable buildings is a perception of technical difficulties during the construction process (Wilson & Tagaza, 2006) and the lack of green product information (Hwang & Tan, 2012)

Notwithstanding additional efforts, most of the current design and decision support tools are inadequate to support and inform the designer during early phases. During the decision making, the designer cannot easily predict the impact of decisions on building performance and cost. Current tools are inadequate, user-hostile, and too incomplete for architects to use during the early design phases of nearly zero sustainable buildings. A disadvantage of most existing tools is that these operate as post design evaluation (Attia et al., 2012).

4.5.3 Awareness and policies.

Knowledge and policies represent another type of sustainability barrier. A lot of barriers are related to lack of knowledge about sustainable technologies (Zhang et al., 2011). The implementation bodies involved in large constructions are often unaware of measures, techniques, and technologies that ensure environmentally benign constructions (India Habitat Centre., 2006). Williams and Dair (2007) found in a research study conducted in England that stakeholders lacked information, awareness, or expertise to achieve the sustainable measures needed in sustainable solution implementation. In some situations, sustainable measures are not of importance because these are not in the stakeholder’s agenda; the stakeholder has no power to enforce or demand sustainable measure, or the stakeholder was not included or was included too late in the development process to implement sustainability measures (Williams & Dair, 2007).

In the specific case of homeowners, Tomkiewicz (2011) found that 70% of homeowners do not believe that their homes harm the environment. The lack of owner awareness leads to situations that leave our sustainability measures because it was not a client requirement (Williams & Dair, 2007).

Finally, legislation and regulations are additional barriers identified by stakeholders. In some cases, complex legislation keeps the implementation of sustainable measures from taking place (Hwang & Tan, 2012). Some stakeholders face situations in which sustainable measures are unavailable, restricted, or not allowed (Williams & Dair, 2007). This type of scenario shows that building regulations and codes need to incorporate sustainable design features for clearance of construction activities (India Habitat Centre., 2006).

Some authors suggest that governments should increase the promotion of sustainable practices. Williams and Dair (2007) affirm that sustainable objectives are often not considered in places where there are no regulatory or policy responsibilities. Zhang et al. (2011) state that there is a need for policy and regulations on green issues government initiatives can promote.

4.5.4 Management.

Stakeholders are aware of the relationship between sustainable practice barriers and prior experience of construction management with sustainable projects. The lack of senior management support is a limitation. Many developers are still reluctant and uncertain about adopting sustainability in their projects due to limited understanding and the pursuit of cost reductions in developing countries such as China (Shi et al., 2013). There is a perception of risk associated when changing from traditional processes of design and construction including different contract forms of project delivery, longer design time using integrated design teams, the introduction of greener and recycled materials, changed site practices and behaviors (Wilson & Tagaza, 2006).

The main challenge lies in that green technologies are usually more complicated and are different from conventional technologies (Wilson & Tagaza, 2006). According to traditional methods and norms, there is a preference for short-term solutions over long-term solutions (Hwang & Tan, 2012). The lack of knowledge of green technology and materials also affect the inclusion of sustainable practices. For instance, a project manager has to deliver the project with the required performance, and unfamiliarity with the performance of green technologies may affect the performance outcome (Hwang & Tan, 2012).

4.6 Sustainable design tools

The design of a sustainable house is a non-intuitive, iterative process. This process requires the participation of experts at early stages of the pre-construction phase and requires coordination and integration from all participants. For these reasons, it is helpful to use support tools to help experts with the accomplishment of certain goals. Every decision made during the pre-construction phase will later have an impact on the construction cost and house performance. Experts support their decisions by using tools such as a checklist, handbooks, of computational tools.

Computational tools appear to be a suitable instrument to support decisions regarding the selection and integration of sustainable components: these can provide detailed information on the thermal performance of buildings before erecting the buildings, thereby allowing objective comparison of different design options under identical conditions.

Building research communities are highly interested in computer-based optimization techniques. One of the reasons of this interest is that every construction project is unique; hence, the optimal design solutions depend on many variables such as climatic data, available technologies and materials, population lifestyle, the age of the building, and its use (i.e., commercial buildings, residential).

Projects also have to meet increasingly stringent quality demands, which are ever more quantifiable performance requirements (e.g., performance-based building codes). To guarantee that buildings indeed meet these demands, increased use of computational tools is inevitable in performance-based building design decision-making (de Wilde & Van Der Voorden, 2004). The intended use of computational tools is to facilitate the project delivery process, mostly during the pre-construction phase, but many authors agreed in some limitations of the existing software, up to the point of being extremely complex. Therefore, the tools become a barrier to the integration of sustainable practices in construction (Attia et al., 2012; de Wilde & Van Der Voorden, 2004). Some authors mention that the tools are not user-friendly, and these tools require a great level of expertise (Purdy & Beausoleil-Morrison, 2001). Furthermore, the continuous development of new tools forces users to handle various tools because a single tool capable of integrating the capabilities of all existing tools is nonexistent.

An estimate of the number of computational tools available for the support of sustainable practices is difficult. Up to 2014, the U.S. Department of Energy hosted a list of Building Energy Software Tools known as the BEST Directory. The 2014 list includes nearly 500 tools. Now, the International Building Performance Simulation Association (IBPSA) hosts the list. The number of computational tools available in the current directory is 300. It is less than the 500 tools of 2014 because the site is still in the process of onboarding all of the past software vendors. Even with all the tools available, a substantial study that identifies the most used sustainable tools by residential designers is nonexistent.

Hendricx (2000) classifies computational tools into modeling tools, design tools, and analysis tools. Modeling tools use computers to represent the evolving ideas as an artifact during the design process. Design tools use the computer to improve the existing design by generating design alternatives. When a computer generates alternatives, the design tool performs automated design. When a machine collaborates to generate alternatives, the given name of this design type is assisted-design. The analysis tools use the computer to evaluate existing buildings or designs by assessing properties and performances.

Often, a combination of tools creates new tools. For example, to achieve the optimal solution with less time and labor while exploring many design options, some authors proposed the use of a simulation-based optimization method. This method consists of using a computer-automated model where a building simulation program coupled to an optimization engine. Thus, the optimization problem is solved using iterative methods driven by optimization algorithms (Ferrara et al., 2014).

4.7 Conclusions

The main goal of this chapter is to review the impact of buildings in resource consumption and then focuses on the integration of sustainable parameters in housing project delivery. The relationship of the sustainable parameters with the construction components are established and the barriers to integrating sustainable practices in the homebuilding industry are identified. The findings from the literature show that the selection of the majority of sustainable parameters takes place during the early stages of the pre-construction phase and that the design process is a component that greatly influences in achieving construction of sustainable housing.

CHAPTER 5 INITIAL MODEL DEVELOPMENT

This research proposes a decision support system (DSS) to assist decision makers in the selection of construction parameters in single-family housing project delivery and to empower stakeholders with a tool for use in the early stages of the delivery process. The methodology to achieve the objectives of this research is in Figure 12; it includes three phases with specific milestones.

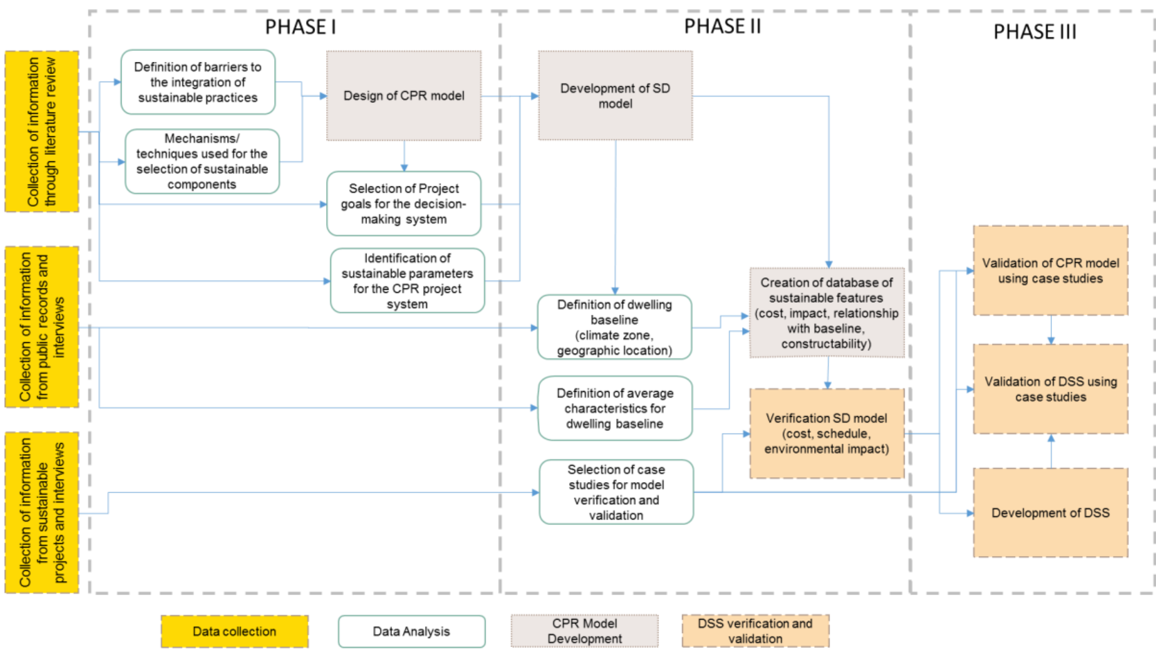


Figure 12. Description of the methodology

A data collection component from the literature composes the first phase of the methodology. The milestone of phase I is the design of the model for selecting construction parameters at the early stages of residential development (CPR). Identifying the integration barriers of sustainable practices in the residential sector took place during this phase; exploration of the mechanisms and techniques used to select sustainable components also takes place during this phase. During the second phase of the research, the collection of information from public records and interviews were used to accomplish the milestone of phase II: the design of the SD model. Finally, during the third phase of the system development, the CPR model and de SD model were integrated into the DSS, and the system was validated using case studies.

In this research, the DSS consists of a combination of computer-based and human-powered system. The computer-based system has two main components: the CPR model and de System Dynamics model. The decision maker interacts only with the CPR model contains while the CPR model interacts with the SD model. Figure 13 represents the Decision Support system and its relationship with the CPR model and the System Dynamics model, of which a further detailed explanation follows.

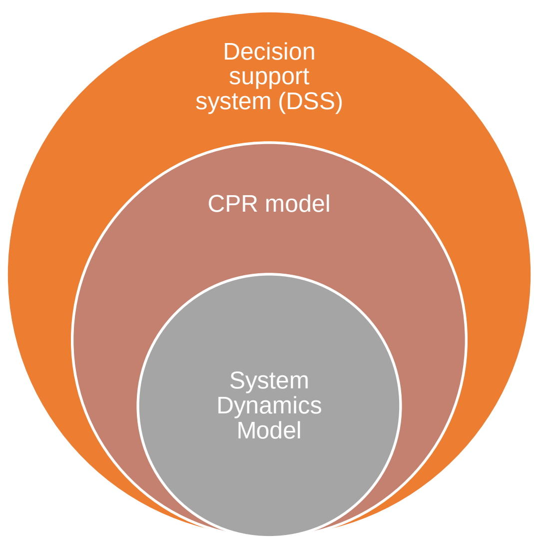


Figure 13. Relationship between the DSS, the CPR model, and the SD model

The proposed decision support system (DSS) is an interactive computer-based system that aids decision makers with the decisions related to the selection of sustainable parameters during early stages of the design process. The definition and use of DSS have changed over the years. For this particular research, the goal is to use suitable technology to improve the effectiveness in the selection of sustainable parameters in housing project delivery.

Using the relationship with the user as classification criteria, categories for DSSs can be passive, active, or cooperative. Another classification uses the mode of assistance as the criterion and differentiates among systems that are communication-driven, data-driven, document-driven, knowledge-driven, and model-driven. According to these definitions, the proposed DSS is a passive and model-driven system. Table 7 summarizes these different classifications.

Table 7. Taxonomy of decision support systems

DSS Taxonomy		**References**
According to the relationship with the user		Haettenschwiler (2001)
Passive	The system aids the process of decision making, but can't produce decision suggestions or solutions.	
Active	The system can produce decision suggestions or solutions.	
Cooperative	The user can modify, complete, or refine the decision suggestions provided by the system before these are sent back for validation.	

Table 7. Taxonomy of decision support systems (continued)

DSS Taxonomy		**References**
According to the mode of assistance		
Communication-driven	More than one person can work on a shared task at the same time.	
Data-driven	Allows access and manipulation of a time series of data.	
Document-driven	Use of unstructured information in a variety of electronic formats.	Power (2002)
Knowledge-driven	Supports problem-solving by using facts, rules, or procedures.	
Model-driven	Assist decision makers by accessing and manipulating a model while using data and parameters provided by the user.	

The DSS is the interface that the decision makers use to interact with the components of the system and to obtain the results from the models. The main element of the computer-based part of the DSS is the CPR model, which this chapter further explains.

5.1 Model for selecting construction parameters at the early stages of residential development (CPR)

The CPR model requires a method for the selection of project goals in the decision-making system. The outcomes from the CPR model are to provide direct stakeholders with results that can be used to make decisions about the selection of sustainable components in the early stages of residential development. Estimated cost, duration, and environmental impact of the alternatives are the basis of these decisions. The CPR model, represented in Figure 14, consists of four main components: external factors, decision-making system, the design and analysis parameters, and the System Dynamics model. Chapter 4 explains the design and analysis parameters; this chapter offers an explanation of the external factors, the decision-making system, and the system dynamics model.

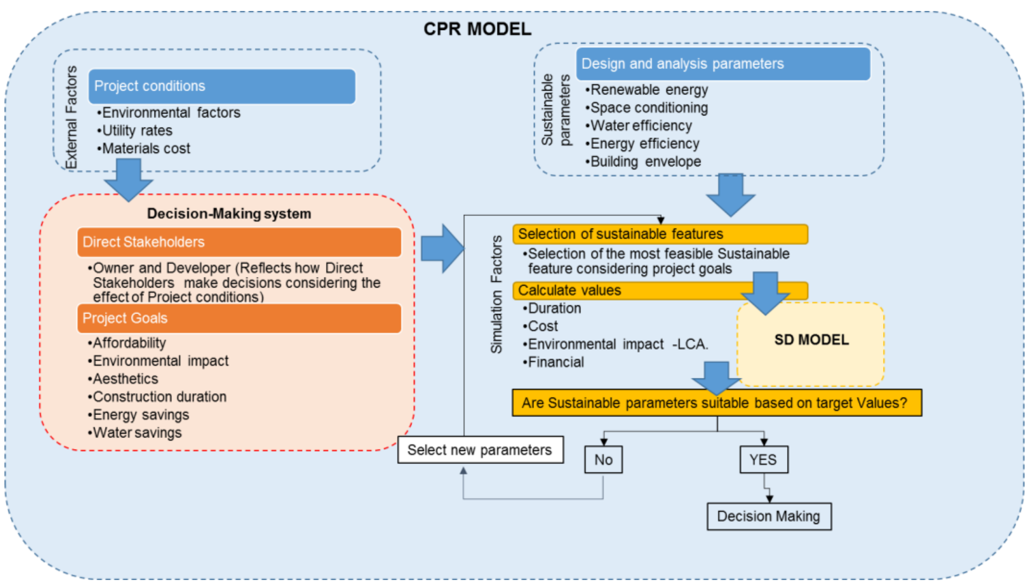


Figure 14. Model for selecting construction parameters at the early stages of residential development (CPR)

5.1.1 External factors.

External factors are those that have an impact on the project but cannot be modified by the stakeholders. The three external factors that modify the CPR model are environmental factors, utility rates, and material cost, as shown in Figure 15. In the CPR model, the external factors that will be considered part of the project are the ones related to project conditions.

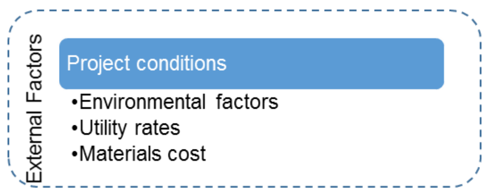


Figure 15. External factors of the CPR model

5.1.1.1 Environmental factors.

The environmental factors in the CPR model are those related to the climate zone and the weather conditions according to the project location. Environmental factors are part of the consideration because they influence the selection of the sustainable features for the building, and they also affect the duration and construction methods during the construction phase.

5.1.1.1.1 Climate Zone

Climate zones are areas that share similar climatic characteristics. The climate zone designations used by the U.S. Department of Energy Building America Program (U.S.

Department Of Energy., 2014) are based on heating degree-days, average temperatures, and precipitation and are intended to help builders to achieve the most energy savings in a home. The Building America Program divides the United States into eight different climate zones: hot-humid, mixed-humid, hot-dry, mixed-dry, cold, very-cold, subarctic, and marine as represented in Figure 16.

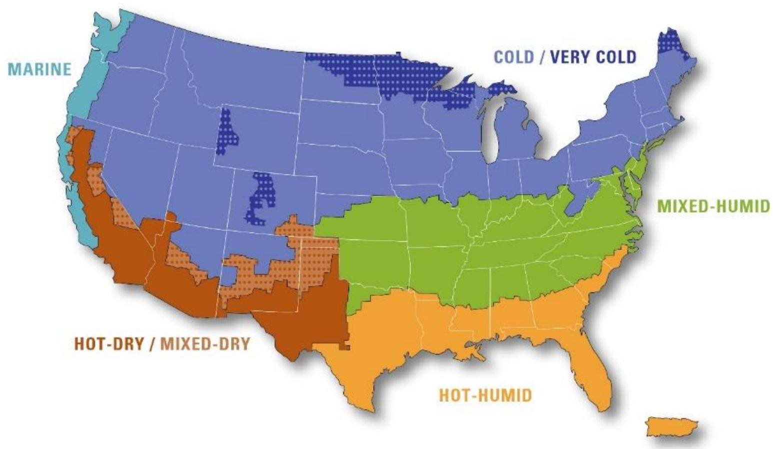


Figure 16. Building America climate zone map.

(Source: U.S. Department Of Energy., 2014)

-

5.1.1.1.2 Weather

Weather is an external factor that varies with the geographical location of the project and can affect the duration of the construction phase and the cost of construction activities. For this reason, contractors usually consider the weather when preparing schedules, cost estimates, and bids (Moselhi, Gong, & El-Rayes, 1997). Due to the effect that the weather has on construction methods, project duration, and labor productivity, this factor is important in the selection of sustainable features and the calculation of cost and duration for the CPR model.

5.1.1.2 Utility rates.

A public utility is a business that supplies an everyday necessity to the public at large (HG. org., 2010). Some examples of public utilities are water, electricity, natural gas, and telecommunications. Utilities typically create a good or service at one location, and then distribute it over a ‘network’ where it is delivered to numerous customers for end use (Geddes, 1998), as a result, public utilities are often natural monopolies because the infrastructure required to produce and deliver a product such as electricity or water is very expensive to build and maintain (Farlex, 2016). Due to the existence of monopolies, public utilities are legally mandated to go through the rate-making process and to a public utility commission to determine the allowable service charges for the provision of their essential service. For this work, the cost of electricity and combustion fuels (e.g., natural gas) and water in the area of the project are the utility rates for the CPR model since these utilities are the ones that sustainable features impact.

5.1.1.3 Material cost.

The 2015 Cost of construction survey published by the National Association of Home Builders (NAHB, 2015) shows that 61.8% of the average home sale price consisted of construction costs. Construction cost is the direct cost associated with the specific activities that are performed to build the house; this doesn’t include the cost of the lot, financing cost, overhead, marketing cost, sales commission or profit. A breakdown of direct costs includes labor costs, material costs, equipment costs, and subcontractor costs.

5.2 The decision-making system.

The decision-making system reflects how external factors affect the perception of direct stakeholders concerning project goals. The stakeholders in a project can fall into the categories of direct and indirect stakeholders, and by definition, are representatives who may have an interest and can make a contribution to the proposed project (Smith & Love, 2004). The decision-making system uses the preferences of the direct stakeholders and establishes the priorities of the project goals. Figure 17 shows a representation of the decision-making system.

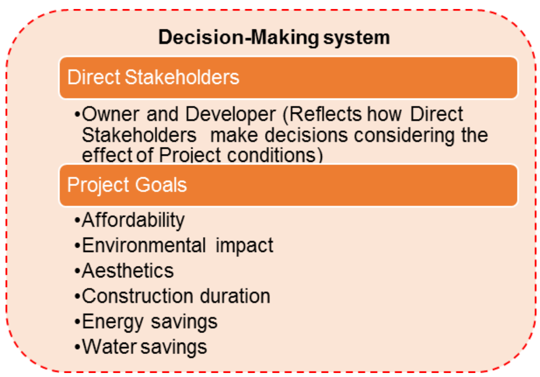


Figure 17. Decision-making system

5.2.1 Direct stakeholders.

The most influencing stakeholders during the early stages of the design process in a residential project are the owner and the developer, and for that reason, the proposed decision-making system includes the perception of them as direct stakeholders. During the early stages of the pre-construction phase, direct stakeholders establish the project goals. Each stakeholder has different perceptions of project goals. To establish the different perceptions of the direct stakeholders, and how these preferences are affected by the external factors, the project goals are required to be ordered by preference and by an importance weight factor given to each goal. During the simulation process, stakeholders have the option of giving their weights.

5.2.2 Identification of project goals.

The first step in assisting decision makers with selecting construction parameters is to lead them in the process of identifying project goals. In this research, a unitary decision maker is considered for a single-family home. The decision problem of selecting the parameters that meet the project goals is reduced to a problem multi-attribute problem under certainty (Keeney & Raiffa, 1993). Decision-making for multi-criteria decisions require the use of a structured decision-making tools (Alexander, 2012). Given that the decision problem in this research is faced with a mix of qualitative and quantitative factors that are take into consideration, decision-making systems use the multi-criteria decision method called the Analytical Hierarchy Process (AHP).

AHP is a particular application in decision making that provides a comprehensive and rational framework for structuring a decision problem, for representing and quantifying its elements, for relating those elements to overall goals, and for evaluating alternative solutions (Saaty & Peniwati, 2013). AHP originated in the 1970 being developed ty professor Thomas Saaty at Wharton Buisiness School in Philadelphia. Over the years, AHP has been the subject of much methodological research and has also been used with success in the solution of many practical problems (Cabała, 2010).

In this research, the decision-making system uses AHP to determine the project goals and to choose among several alternatives with qualitative and quantitative factors.

The AHP consist of four steps (Saaty, 2008):

1. Describe the decision problem in detail, including its objectives, criteria, and sub-criteria and build the AHP hierarchy.

2. Rate the relative importance of these criteria using pair-wise comparisons.

3. Rate each potential choice using pairwise comparisons of the choices.

4. Determine the relative importance weight of each factor.

For the first step, the decision problem subdivides into a hierarchy of sub-problems. The decision problem aims to choose sustainable parameters under five criteria. Figure 18 shows the hierarchy for the problem with the goal, the criteria, and the relationship with the alternatives.

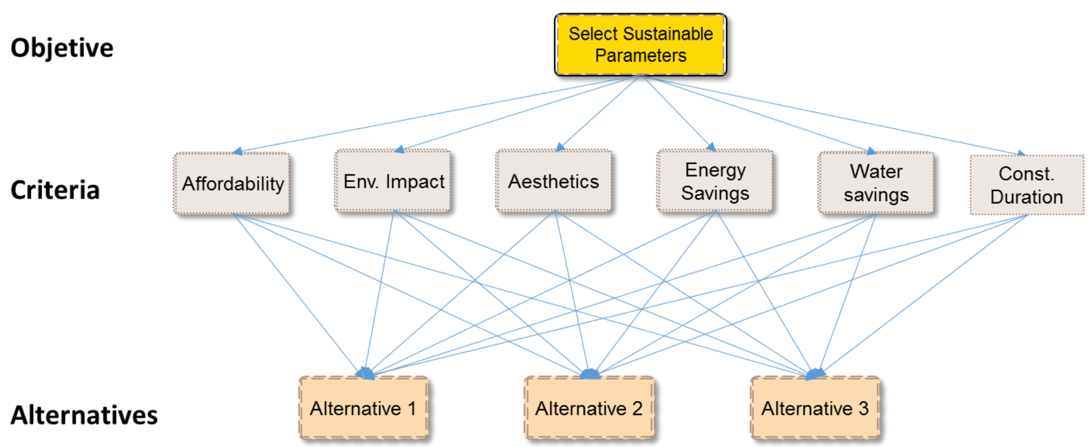


Figure 18. AHP hierarchy for the selection of project goals

After building the hierarchy, decision makers can systematically evaluate the elements by comparing them to each other two at a time according to their impact on the hierarchical element directly above it. Pairwise comparisons are fundamental in the use of the AHP. The decision makers must judge the main criteria by comparing them in pairs for their relative importance by using the fundamental scale proposed by Saaty (Saaty, 2008). The fundamental scale, shown in Table 8, ranges from one to nine, where one implies that the two elements are equally important and nine implies that one element is extremely more important than the other one.

Table 8. Fundamental scale of absolute numbers

Intensity of importance	Definition
1	Equal importance
2	Weak or slight
3	Moderate importance
4	Moderate plus
5	Strong importance
6	Strong plus
7	Very strong or demonstrated importance
8	Very, very strong
9	Extreme importance
Reciprocals of above	If activity i has one of the above nonzero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i.

The result is a comparison matrix of n-order, where n is the number of compared elements. The number of judgments needed for a particular matrix is n(n-1)/2 because it is reciprocal, and the diagonal elements are equal to unity. Table 9 shows an example of a pairwise comparison matrix for the criteria concerning the selection of sustainable parameters. Each entry a_{jk} represents a comparison between two elements, j on the left side of the matrix and k on the top, i.e., the entry $a_{1,2}$ is the result of the comparison between Affordability and environmental impact (4 times) and is read as "Affordability is moderately more important than environmental impact". Consequently, the reciprocal value is entered in the $a_{2,1}$ entry (1/4 times).

Table 9. Pairwise comparison matrix for selecting project goals

Pairwise comparison matrix						
	n=	6	Ri	1.24		
	Affordability	Env. Impact	Aesthetics	Const. Duration	Energy efficiency	Water efficiency
Affordability	**1**	4.00	1.00	4.00	4.00	4.00
Env. Impact	0.25	**1**	0.25	1.00	1.00	1.00
Aesthetics	1.00	4.00	**1**	4.00	4.00	3.00
Const. Duration	0.25	1.00	0.25	**1**	1.00	1.00
Energy efficiency	0.25	1.00	0.25	1.00	**1**	1.00
Water efficiency	0.25	1.00	0.33	1.00	1.00	**1**

In making the comparisons, the decision makers can use concrete data about the elements, but they typically use their judgments about the relative meaning and importance of the elements. It is the essence of the AHP that human judgments, and not just the underlying information, can be used in performing the evaluations (Saaty, 2008). The AHP converts these evaluations to numerical values that can be processed and compared over the entire range of the problem. A numerical weight or priority is derived for each element of the hierarchy, allowing a rationally and consistently comparison of diverse and often incommensurable elements. This capability distinguishes AHP from other decision-making techniques.

Once the pairwise comparison matrix exists, it is possible to derive a normalized pairwise comparison matrix by making the sum of the entries on each column equal to 1. Each entry $\bar{a}_{jk}$ of the normalized matrix is computed as

$$\bar{a}_{jk} = \frac{a_{jk}}{\sum_{l=1}^{m} a_{lk}} \qquad (1)$$

The final step of the process includes numerical priority calculations for each of the decision alternatives. These numbers represent the relative ability of the alternatives to achieve the decision goal to allow a straightforward consideration of the various courses of action. Table 10 shows the normalized pairwise comparison matrix and the numerical weight priority derived for the selection of project goals. The weight vector is built by averaging the entries on each row of the normalized pairwise comparison matrix. The result is an n-dimensional column vector computed as

$$w_j = \frac{\sum_{l=1}^{m} \bar{a}_{jl}}{n} \qquad (2)$$

Table 10. Normalized pairwise comparison matrix and weight vector for selecting project goals

	Normalized pairwise comparison matrix						Criteria weight vector
	Affordability	Env. Impact	Aesthetics	Const. Duration	Energy efficiency	Water efficiency	
Affordability	0.154	0.286	0.154	0.138	0.129	0.222	0.1804
Env. Impact	0.038	0.071	0.038	0.138	0.129	0.056	0.0785
Aesthetics	0.154	0.286	0.154	0.138	0.129	0.222	0.1804
Const. Duration	0.154	0.071	0.154	0.138	0.129	0.222	0.1447
Energy efficiency	0.462	0.214	0.462	0.414	0.387	0.222	0.3601
Water efficiency	0.038	0.071	0.038	0.034	0.097	0.056	0.0559

The consistency ratio (CR) is calculated and verified. The consistency ratio (CR) is calculated using the formula, CR = CI/RI in which the consistency index (CI) is, in turn, measured through the following formula:

$$CI = \frac{\lambda max - n}{n - 1} \qquad (3)$$

λmax : maximum eigen value of pairwise comparison matrix

The preferred levels for consistency are 0.0 for a 3x3 matrix, 0.08 for a 4x4 matrix, and 0.1 for other matrices (Saaty, 1994) (Drake, 1998).

5.2.3 Project goals.

The model uses a set of project goals from the information available in the literature about sustainable residential projects. Other authors have proposed different sets of goals: the United States Department of Energy (DOE) used six goals, or categories, to identify a DOE Challenge Home (DOE, 2012): Comfort/Quiet, Healthy Environment, Enhanced Durability, Advanced Technology, Quality Construction, Energy Efficiency. The Passive

House Institute US (PHIUS) has a different set of goals: Comfort and health, Quality, Cost-effective, Efficient, Resilient (PHIUS, 2016), and the DOE Race to Zero Competition (e.g., affordability, comfort, health, durability, disaster resilience, marketability) (DOE, 2017). The CPR proposes a combination of these goals and adds construction duration as a goal that considers how efficiently and easily can construction and installation be performed on the project. The basis of the selection of the CPR model goals are the characteristics of the sustainable parameters that are measurable at the early stages of residential project development. A comparison of the project goals defined by the above authors and Table 11 summarizes the project goals defined for the CPR model.

Table 11. Project goals established by different methodologies

DOE Challenge Home	Passive House Institute	DOE Race to Zero Competition	CPR model
Comfort/Quiet Healthy Environment Enhanced Durability Advanced Technology Quality Construction Energy Efficiency	Cost-effective Quality Comfort and health Efficient, Resilient	Affordability Comfort Health, Durability Disaster resilience Marketability	Affordability Environmental impact Aesthetics Construction duration Energy efficiency Water efficiency

The importance that different stakeholders give to project goals varies significantly from one project to another. Hence, the CPR model uses project goals as input. Due to the endless possibilities of establishing project goals, a literature review was conducted to select a list of goals that align with the purpose of sustainability and that have an impact on the expected outcomes of the project (e.g., cost, duration, environmental impact).

The following presents a definition of each of the project goals used for the CPR. Table 12 summarizes the key references and concepts associated with each definition.

Table 12. Concepts and key references associated with project goals

Goal	Concept	Key references
Affordability	Affordability	(DOE, 2017)
		(Wallbaum, Ostermeyer, Salzer, & Escamilla, 2012)
	Cost-effective	(PHIUS, 2016)
	Economic efficiency	(Iwaro, Mwasha, Williams, & Wilson, 2014)
		(Jadid & Badrah, 2012)
	Material cost	(Iwaro et al., 2014)
Environmental impact	Environmental impact	(DOE, 2012), (DOE, 2017)
	Quality	(DOE, 2012)
		(PHIUS, 2016)
Aesthetics		(Iwaro et al., 2014)
		(Jadid & Badrah, 2012)
Construction duration	Constructability	(DOE, 2012)
	Resilient	(PHIUS, 2016)
	Workability	(Iwaro et al., 2014)

Table 12. Concepts and key references associated with project goals (continued)

Goal	Concept	Key references
Energy efficiency	Energy efficiency	(DOE, 2012)
		(Iwaro et al., 2014)
	Efficient	(PHIUS, 2016)
	Renewable energy	(USGBC, 2010)
	Material-efficient framing	(USGBC, 2010)
Water efficiency		(USGBC, 2010)

5.2.3.1 Affordability.

The description of the concept of affordability is often in terms of the ability of a purchaser to pay for the cost of something. The basis of measures of housing affordability usually relates to the assumptions of what housing is worth (O'Dell, Smith, & White, 2004). The conventional public policy indicator of housing affordability in the United States is the percent of income spent on housing (Schwartz & Wilson, 2008). Housing expenditures that exceed 30 percent of household income are historically an indicator of a housing affordability problem (Linneman & Megbolugbe, 1992).

The concept of affordable housing has been used recurrently to refer to housing units that are affordable by that segment of society whose income is below the median household income (Burt, 2001; Crowley, 2003; Downs, 2004; Wallace, 1995). Families who pay more than 30 percent of their income for housing are considered cost burdened and may have difficulty affording necessities such as food, clothing, transportation, and medical care. The conventional 30 percent of household income that a household can devote to housing costs before the household is said to be "burdened" evolved from the

United States National Housing Act of 1937 (Schwartz & Wilson, 2008). The National Housing Act of 1937 created the public housing program, which is a program that serves families in the lowest income group. Although the concept of affordable housing is commonly associated low-income households, an affordable house can be defined as a house that a family group can acquire within a given period, which generally ranges from 15 to 30 years (Wallbaum et al., 2012). This period connects directly to the acquisition capacity of the group and the financial support that they can obtain in terms of loans, credits, and subsidies (UN Habitat, 2009).

In this document, affordable housing is housing that is adequate in standard and cost for the median household income (MHI) of the location and the for the targeted market segment (s).

5.2.3.2 Environmental impact.

The construction of buildings consumes significant amounts of energy and produces emissions and waste (Guggemos & Horvath, 2006). Buildings account for a large environmental impact during their life cycle, which includes the production of materials, construction, operation, maintenance, disassembly, and waste management (Gustavsson & Joelsson, 2010). Sustainable efforts in residential buildings need to focus not only on the reduction of energy consumption but also on the impact generated by the materials used during the life cycle of the building. There are several ways to measure environmental impact; one is carbon dioxide release from the energy used to manufacture the materials and to produce the energy required for the operation of the building (Harris, 1999).

5.2.3.3 Aesthetics.

Aesthetics is a philosophical branch that deals with the nature of art, beauty, and taste while creating and appreciating beauty. In the housing research literature, there is a remarkable consistency about the importance of the aesthetics of the development and dwelling unit in promoting resident's satisfaction (Francescato, Weidemann, Anderson, & Chenoweth, 1979). Furthermore, aesthetics is a primary factor in the selections of internal and external finishing materials for construction (Jadid & Badrah, 2012).

The beauty of a component is difficult to quantify. Different users will have different opinions since the aesthetic experience suggest that it consist of sensory, formal, and associational values (Lang, 1987). Nevertheless, the aesthetic aspect of components and materials is an important aspect of the analysis of the environmental impact of the design of buildings and open spaces (da Luz Reis & Lay, 2010). Environmental beauty and visual impact have been adopted by the Supreme Court of the United States as an adequate base for development. Specifically, the "National Environmental Protection Act" of 1969, determines a thorough evaluation of the effects of major projects in the environment, requires consideration of visual impacts (da Luz Reis & Lay, 2010). Moreover, the American courts sustain that environmental beauty is of legitimate public interest and this must be based on the preferences of the general public and not on the personal tastes of government officials (Castro-Lacouture & Ramkrishnan, 2008; Stamps, 2013).

5.2.3.4 Construction duration.

The duration of the construction of the project is affected by the ease to construct structures and the elements that are part of the structure. In this document, the construction duration is a used as an element that measures the constructability of the project. Various sources define constructability as a project management technique used to review construction processes and to identify obstacles before a building a project to reduce and prevent errors during the construction and operation phases of such project (Fischer & Tatum, 1997; Jergeas & Put, 2001; O'Connor, Rusch, & Schulz, 1987). Furthermore, the Construction Industry Institute (CII) defined constructability as the "optimum use of construction knowledge and experience in planning, design, procurement, and field operations to achieve overall project objectives" (CII 1986). Some authors extend the integration of such construction knowledge and experience to the maintenance and decommissioning phases of a project consistent with overall project objectives (Gambatese, Pocock, & Dunston, 2007).

On the other hand, other authors use the definition of constructability to describe a project property similar to operability and maintainability (Gambatese et al., 2007). Given that there is a continuum in the level of constructability rather than just optimum, constructability has also been defined as a project property that "reflects the ease with which a project can be built and the quality of its construction documents" (Dunston et al. 2003).

5.2.3.5 Energy efficiency.

Efficient energy use, sometimes called energy efficiency, is the goal to reduce the amount of energy required to provide products and services. For example, insulating a home allows a building to use less heating and cooling energy to achieve and maintain a comfortable temperature. Installing fluorescent lights, LED lights, or natural skylights reduces the amount of energy required to attain the same level of illumination compared to using traditional incandescent light bulbs. Improvements in energy efficiency are generally achieved by adopting a more efficient technology or production process or by applying commonly accepted methods to reduce energy losses.

There are many motivations to make buildings more energy-efficient: reductions in energy use, energy cost, fossil fuel consumption, and reduction in greenhouse gas emissions, to mention some examples. Energy efficiency means to use less energy to provide the same service. In the case of buildings, energy efficiency is the result of minimizing the needs of the energy used for cooling, heating, and lighting.

Implementing different strategies can lead to energy efficiency. For example, there is a growing movement in Germany, Austria, and Switzerland to build passive houses based on the requirements of the Passive House Institute (PHI). The general criteria of PHI include space heating demand, space cooling demand, primary energy demand, airtightness, and thermal comfort (PHIUS, 2016).

5.2.3.6 Water efficiency

Water is one of our most undervalued resources. From the non-renewable resources consumed by the residential sector, water is the most essential to ensure human life. Water is the main constituent of the human body, which contains from 55% to 78% of water depending on body size (Jéquier & Constant, 2009). On July 28, 2010, the United Nations General Assembly declared safe and clean drinking water and sanitation a human right essential to the full enjoyment of life and all other human rights.

Water efficiency or water use efficiency refers to the accomplishment of a function, task, process, or result with the minimal feasible amount of water (EPA, 2016), which means doing more with less water or using less water to get the same job done. Water efficiency normally relies on well-engineered products and fixtures like reduced water use dishwashers, or low-flow toilets and showerheads.

Water efficiency can lead to significant savings in money and energy. The EPA estimates that by using water- (and energy-) efficient WaterSense-labeled fixtures and ENERGY STAR-rated appliances, the average family could reduce their water and energy use by up to 20 percent and save up to $380 per year (EPA, 2016).

5.3 The System Dynamics model

The starting point in any simulation design is to identify the system of study and define the problems based on the real world (Robinson, 2004). By using various assumptions and simplifications, the real-world problem reduces to a conceptual model for simulation. The choice of a simulation paradigm imposes the set of core or fundamental assumptions and simplifications (Lorenz & Jost, 2006). A literature review of available simulations paradigms led to three multi-paradigm simulation methodologies that seem reasonable to simulate complex socio-technical systems: System Dynamics (SD), Agent-Based Modeling (ABM), and DES Discrete Event Simulation (DES). A set of modeling assumptions accompanies each paradigm.

SD is a feedback-based simulation paradigm that macroscopically models system behavior. The modeler explicitly assumes that rates, levels, and feedback loops compose the world when using SD as a simulation paradigm (Meadows, 1989). ABM is a modeling type that focuses on representing an agent with individual behavior, and it is used by the modeler to observe the emergent behavior produced from the interaction of a population of those agents. ABM is used to describe and demonstrate how the interaction of independent agents create collective phenomena, and to identify single agents with behaviors that have a predominant influence on the generated behavior (Lorenz & Jost, 2006). Lastly, DES is an event-based simulation in which a system possesses, at any time, a state that discrete events trigger changes over time (Behdani, 2012). The perspective in DES is on multiple events; an event is an instantaneous occurrence that can change the system state. Typical DES applications are the so-called queuing models in which customers arrive from time to time and join a queue or waiting line. Customers eventually receive service, and finally, they exit the system. DES modeling is appropriate for systems in which system-state-changes occur only at discrete points in time and form operational logistics problems that will undergo optimization and require short time horizons (Lorenz & Jost, 2006).

There are major differences in the modeling styles of the above paradigms. Table 13, adapted from Lorenz and Jost (2006) and Behdani (2012), summarizes characteristics of the three simulation paradigms.

Table 13. Summary of main characteristics of three simulation paradigms

System Dynamics (SD)	Discrete-event Simulation (DES)	Agent-based Simulation
System-oriented	Process-oriented	Individual-oriented
Focuses on modeling system observables	Focuses on modeling the system in detail	Focuses on modeling the entities and their interactions
“Feedback loops” driver the system’s dynamic behavior	“Event occurrences” drive the system’s dynamic behavior	“Decisions and interactions of the agents” drive the system’s dynamic behavior
Stock and flow are the system’s mathematical formalization.	Event, activity, and process are the system’s mathematical formalization.	Agent and environment are the system’s mathematical formalization.
Continuous and discrete time.	Discrete handling of time.	Discrete handling of time.

The comparison helps to select the paradigm that offers the most accurate representation of the problem based on the real world. The three simulation paradigms have different orientations and scopes, but sustainable parameter selection is an iterative process that requires analysis at a macroscopic level, which the use of feedback loops and causal loop diagrams within the SD methodology better represents.

5.3.1 Applicability of system dynamics

System dynamics (SD) is a simulation methodology that combines theory, methodology, and philosophy to understand the dynamic behavior of complex systems. Then, the understanding of the system is used to draw casual loop diagrams (CLD) to see relationships between the parts and interactions thereof. Casual loop diagrams are useful to understand a system's mechanisms and feedback links. Much of the art of SD modeling is about discovering and representing the feedback process that determines the dynamics of a system (Hjorth & Bagheri, 2006). Figure 19 shows a CLD for home affordability; it represents the effect of annual expenses and mortgage payments on the maximum price that a family can afford according to their median family income.

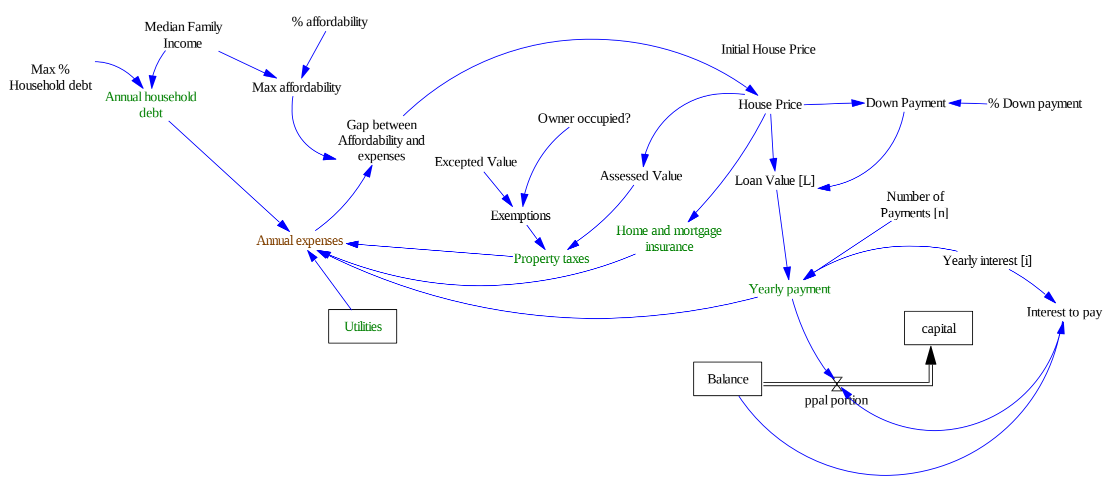


Figure 19. Casual loop diagram for home affordability

SD applicability lies in building and running simulations models to analyze system performance under different scenarios. The methodology allows changing variable values or structures, by changing the information links in a system, to see how the basic reference modes of the system vary through time. SD was initially applied to the field of management to analyze how successes and failures were affected by corporate policies. As a mathematical modeling technique, SD can be applied to understand the performance over time of a complex system, and it can be implemented to the modeling of systems in various disciplines, besides the ones that are related to social sciences (Thompson & Bank, 2010).

The construction industry deals with the interaction of multiple variables and agents. The industry faces complex problems that are difficult to solve through linear causal thinking. Moving from a static, one factor-at-the-time analysis to a dynamic whole-system analysis addresses said issue. The construction industry can use SD to analyze project issues during pre-construction (Brahme, Mahdavi, Lam, & Gupta, 2001), construction (L. Shen, Wu, Chan, & Hao, 2005), and post-construction (T.-S. Shen, 2005; Thompson & Bank, 2010) phases.

Project management is the area in the construction industry that most commonly uses SD. For example, project management uses SD to study the effects of project personnel changes during the design stage of a construction project (Chapman, 1998), as well as to understand change and rework in a construction project management system (Love, Holt, Shen, Li, & Irani, 2002). Project management also uses SD to study the cause-effect relationships that may be responsible for time and cost over-runs in infrastructure projects (Ogunlana, Li, & Sukhera, 2003) and to evaluate the negative impacts of error and changes on construction performance for negative iterative cycles (Lee & Peña-Mora, 2005). Another example of how project management uses SD is to study the economic and environmental impacts of construction processes for change and error management (Lee & Peña-Mora, 2005).

Construction project management has also implemented SD to control time and cost. For example, project management used SD to propose a model that quantifies productivity loss by recognizing the interaction of work activities as well as to graphically illustrate disruptive mechanisms (Ibbs & Liu, 2005). The model assisted acceleration, delay, and disruption claims; quantifies and portrays indirect productivity losses; determines that activity that causes the largest amount of delay; and determines the activity that takes the most time in a particular project.

Another example is the dynamic planning and control methodology (DPM) for design/build fast-track civil engineering and architectural projects developed by integrating SD with the graphical evaluation and review technique, axiomatic design concepts, and engineering concepts (Peña-Mora & Li, 2001). SD was applied to analyze the causality links of relevant factors in the construction system and to identify important variables that determine the success of a particular overlapping strategy to create a dynamic project plan that can absorb changes in the project schedule without creating major interruptions.

Construction projects have used SD to analyze delay claims, disruption claims, and dispute resolutions. For example, a conceptual and mathematical model, which evaluates alternative dispute resolution (ADR) investments, provides a decision framework that accounts for the uncertainty in estimating the ADR investment cash flows during the project planning phase (Menassa, Peña-Mora, & Pearson, 2009). Another SD analysis example is a model adopted to represent the dynamic complexities conflict origin, conflict escalation, interaction between conflicts, and dispute avoidance and resolution techniques (DART) (Ng, Peña-Mora, & Tamaki, 2007).

5.3.2 SD in residential construction

The residential construction area of sustainable development has implemented SD. Building design strategies to predict and reduce the environmental loads for the several types of construction and building materials (Matsumoto, 1999) are an example of SD implementation. Other SD implementation examples are the construction life cycle analysis of residential buildings (Marzouk, Abdelhamid, & Elsheikh, 2013) and the mid and long term impacts of green building policies on the greenhouse gas (GHC) emissions stock (Onat, Egilmez, & Tatari, 2014).

Some cases have integrated software with the available SD methodology tools. An example of this integration is the proposed approach for sustainability assessment of urban residential development using Geographical Information System (GIS), SD, and 3D visualization. The preceding integrated tools allow exploring housing equilibrium by using sustainability indicators; these tools also explore economic, social, and environmental features on residential buildings. Furthermore, it is possible to visualize the simulation data in GIS technology with integrated tools (Xu & Coors, 2012).

5.4 SD and CPR model interactions

The system dynamics model uses the inputs from the CPR model and simulates possible combinations of sustainable features to calculate the values for duration, cost, and environmental impact. Figure 20 shows a representation of inputs for the SD model.

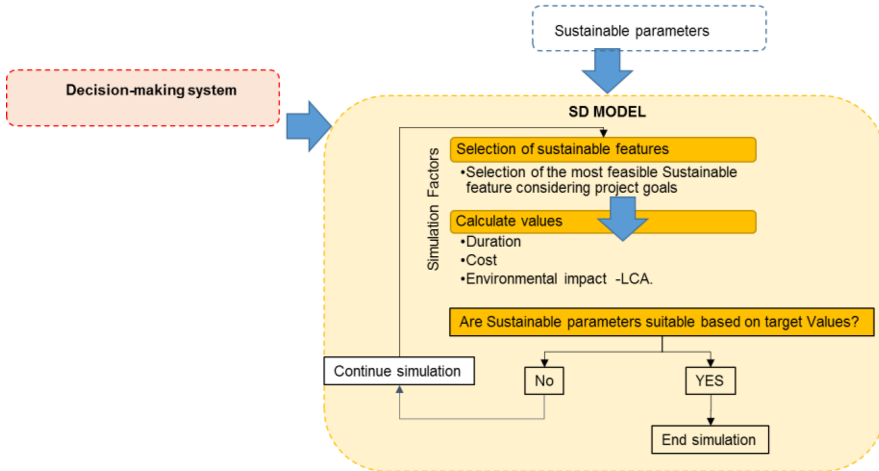


Figure 20. Inputs for the SD model

The sustainable parameters are pre-established for the model according to existing features (e.g., solar panels, window systems, water heaters) but can be modified by the stakeholders according to specific conditions for the project. The design and analysis parameters used in the CPR model fall into five categories that Figure 11 represents, and section 4.3 explains.

The SD uses the inputs from the CPR for the simulation. The simulation process occurs in the background in six steps illustrated in Figure 21. First, an excel file named Par_CPR.xls acquires the information from the CPR model. Second, the dataset file CPR_data.vdf is created using the CPR_form.frm file that tells Vensim how to import the spreadsheet files into the model. Third, the data is imported and assigned to the SD model variables. Fourth, the Vensim software runs the simulation, and an output Vensim data format file stores the simulation results and converted data, vdf file. Fifth, an excel file is created with the results of the simulation, and finally, the results are acquired by the CPR model to continue with the process.

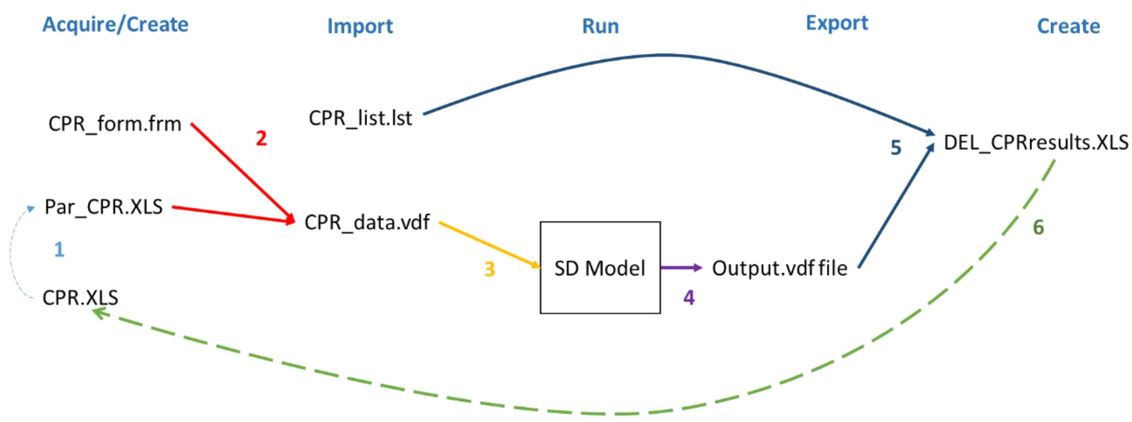


Figure 21. CPR model and SD model interaction

Calculations under the influence of project conditions are made with the resulting values from the system dynamics simulation, which are then subject to comparison with target values for cost, time, and environmental impact of users. The system dynamics model uses qualitative and quantitative data. This data is used to create equations in the system dynamics model to calculate the outputs for the decision support system. Figure 22 shows the CLD that represents the CPR model.

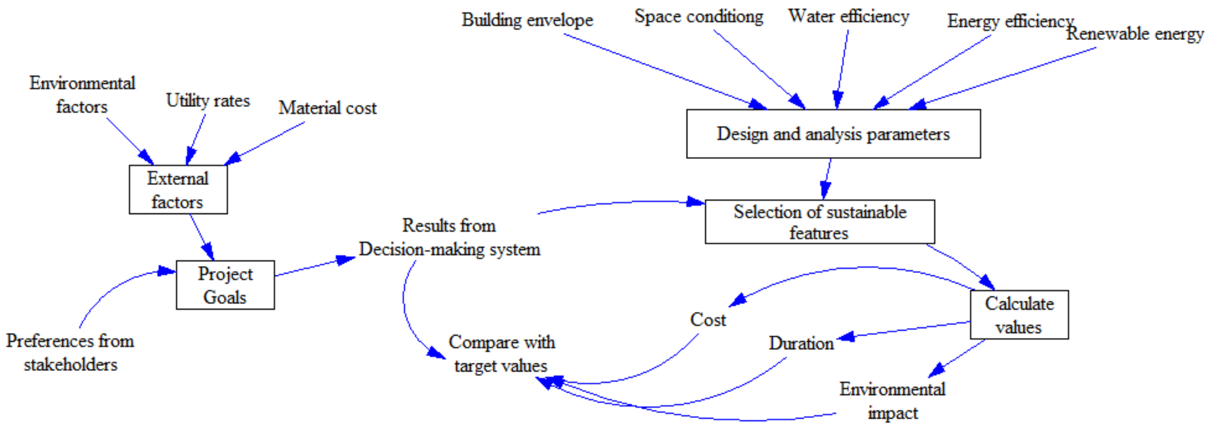


Figure 22. SD representation of the CPR model.

5.5 Further model development

It was a challenge to create an exploratory model from the literature review that could represent the real system, be intuitive to use, and which decision makers could use during the early stage of the project development. Residential construction experts reviewed the exploratory model during semi-structured interviews. The knowledge gathered in the interviews was used to add missing structures to the model and to test the behavior and the structure of the model.

5.5.1 Semi-structured interviews.

The instrument used for data collection consists of semi-structured interviews with experts in the field of residential construction as well as experts in construction sustainable practices. The interviews intended to verify literature review results and to accomplish the following objectives: 1) verification of key sustainable parameters in the housing delivery process, 2) identification of mechanisms and techniques to select sustainable components in the local homebuilding industry, and 3) validation of the CPR model.

The respondents participated in an initial interview and one follow-up interview. The data was collected from semi-structured interviews because participant feedback was necessary to refine the system of the proposed decision support system. APPENDIX A includes the questionnaire of the interviews.

The responses from the subjects were analyzed using grounded theory and the phases that follow. Phase 1: Data collection from semi-structured interviews; Phase 2: Note Taking During Interviews; Phase 3: Coding; Phase 4: Memoing (collections of codes of similar content that allows grouping data), and Phase 5: Sorting and Writing.

The study included interviews with six experts in the field. According to literature, there is no minimum number of interviews, but similar researchers used between four and six subjects to gain the perspectives of experts in the field (Luna-Reyes, 2003; Ozcan-Deniz, 2011; Rich, 2003).

The first interview established the veracity of the information found in the literature review and to gather information on decision making during the process. The answers to the first interview served the following purposes:

- To design the sequence and steps required for the DSS.
- To establish key sustainable parameters in the delivery process.
- To validate the structure of the DSS and the SD model (structure verification test, parameter verification test, and boundary-adequacy test).

- To identify the computational tools and training in sustainable development practices used by the experts in single-family housing design in the area where the study took place.
- To identify the perceptions of the expert about the market for sustainable housing and the availability of information about the added cost associated with building sustainable homes.
- To identify the barriers perceived by the experts in the single-family market for the implementation of sustainable practices.

Each expert was individually interviewed and took place on different dates over one month, which allowed implementing the suggestion from the experts to the exploratory model after each interview. Consequently, the participants observed a model that already included suggestions from the previous participant.

The DSS development took into account the most significant findings of the interviews. First, the experts agreed that there are different relationships with decision makers depending on project types. The designer must relate in some projects with the end-user, for example, when the design is a custom project for a private owner. In contrast, in other project types, the relationship of the designer is with a developer whose objective is project development focusing on a type of client established by the market to which the product targets. Although each case is different, interests depend on the type of relationship. For example, the developer-designer relationship emphasizes interest on a tight budget and ensuring that the products will sell because profitability is of utmost importance. In the case of the homeowner-designer relationship, interests focus on amenities, aesthetics, and space distribution. In some cases, budget is not a project limitation. Therefore, the model considers that the decision maker type varies, and the decision-making process should be flexible.

Another finding is the knowledge type on issues of sustainable development practices. Given that the participants are experts in the metro Atlanta area, most of them are familiar with the EarthCraft program. Some know about LEED certification but stated that LEED involves tremendous amounts of paperwork. Others mentioned practices such as wellness within your walls, ICC 700 National Green Building Standard™, and passive house design and construction. The preceding leads to the conclusion that there is no consensus on the type of sustainable practice in the sector and mandates a flexible model in the face of the different types of existing practices and the new ones that may arise in the future. The decision-making module reflects the preceding, which includes the proposed goals that are measurable in the early stages of the design process. Furthermore, the module can include other goals at a later time as long as the goals are measurable and comparable in the early stage of project development.

Likewise, interviewed experts state that computational tools implemented in the simulation and design stage are AutoCAD, SketchUp, Manual J, Manual D, and REScheck. There was mention of other programs such as RESNET HERS Certification, BPI Certification, and Revit, but only in one case, and not necessarily by the same participant.

Upon asking the experts if there is a market for sustainable homes in the Greater Atlanta area, they all agree that the market is incipient, which they perceive to be between 3% and 8%. Concerning the above, the participants believe barriers exist in the implementation of sustainable parameters in single-family housing. Among the mentioned barriers are low utility costs, which decreases motivation to lower utility consumption because home-owners "do not feel too much pain." They also mention the existence of other conditions that increase the cost of housing, such as the high demands of the energy code that mandates reducing costs of materials to comply with codes while remaining competitive in the market. Regarding financing, the interviewees mentioned that banks do not lend money for elements such as solar panels or additional investment in insulation because the appraisals do not reflect the added value of the additional investment.

On the other hand, interviewees mention some opportunities such as owners increasingly seeking the introduction of sustainable elements, the cost of sustainable elements decreasing over time, and popular remodeling and reconstructions tv programs commonly including these elements; all of which generate market interest in sustainable elements. Also, some government agencies advance efforts to stimulate these practices through tax credits or regulations such as the recent high-performance building ordinance of the City of Decatur. The ordinance requires all new residential and commercial buildings to have a certification under an existing building program (i.e., Silver Level National Green Building Standard-ICC 700-2012; Any Level LEED for Homes; Any Level Certification EarthCraft House, EarthCraft Renovation, or EarthCraft Sustainable Preservation; Any Level of Certification and Green Globes- 3 Globes Certification Level).

In the second round of interviews, which took place one month after the first round of interviews, the same experts answered questions about the SD model and the DSS support system. The experts reviewed the exploratory model and made suggestions. They perceived that one of the greatest contributions of the DSS was the definition of project goals because other systems do not do so, which delimits the project scope and gives clarity to both parties on project expectations. Another contribution is that SD is easy to use, and it uses the widely known interface Microsoft Excel. The second round of interviews helped refine and validate the exploratory model, as well as to review possible additional aspects to include in it.

5.6 The proposed SD model

Three parts simulate the cost and environmental impact of the project for 30 years using time steps of one month fragment the SD model simulation. The monthly financial cost in Figure 23 uses the initial house cost (IHC), the percentage of down payment (dpp), the loan period (y) and the annual percentage rate (APR) to calculate the financing cost for the alternative. The yearly home expenses, shown in Figure 24, result from the calculation that uses the annual utilities, the debt to income ratio (DTI), the initial house cost (IHC), and the home insurance. Finally, the social cost of carbon emissions is estimated using the global warming potential (GWP) of the operating and embodied energy and the revised social cost of CO2 (Interagency Working Group, 2013), 2010-2050 in 2019 dollars per metric ton of CO2, using the model illustrated in Figure 25. APPENDIX B shows the system dynamics functions generated in Vensim.

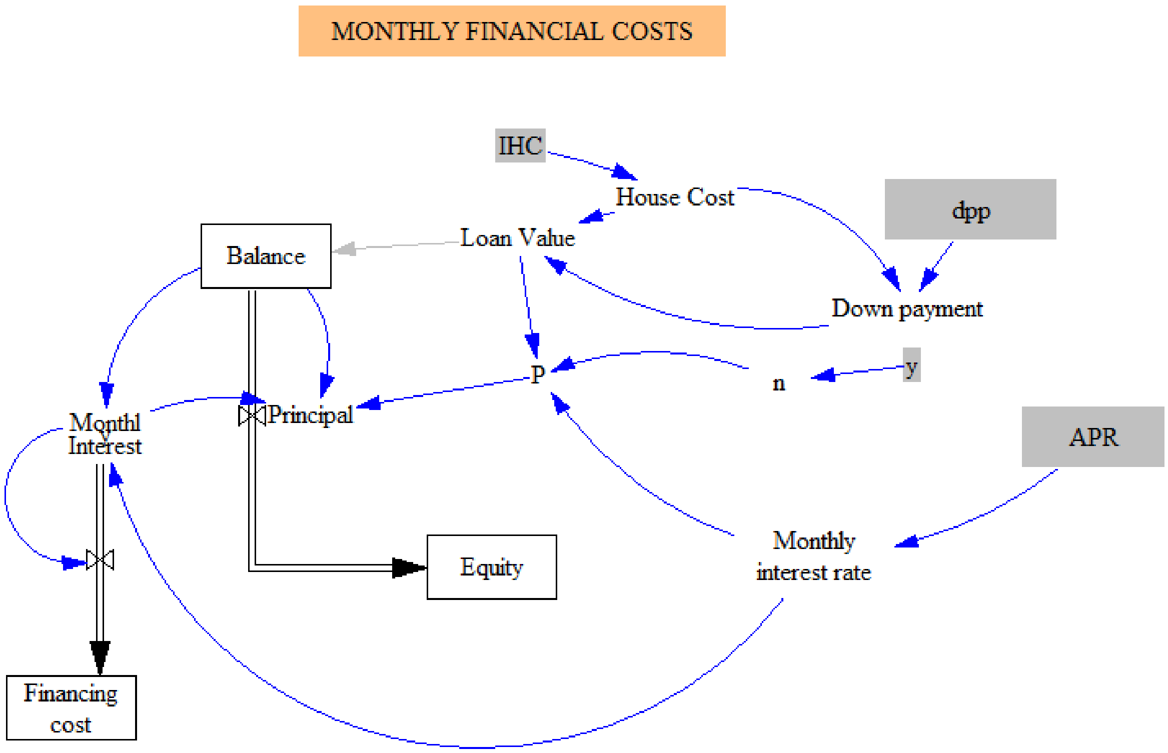


Figure 23. Proposed SD model for monthly financial costs

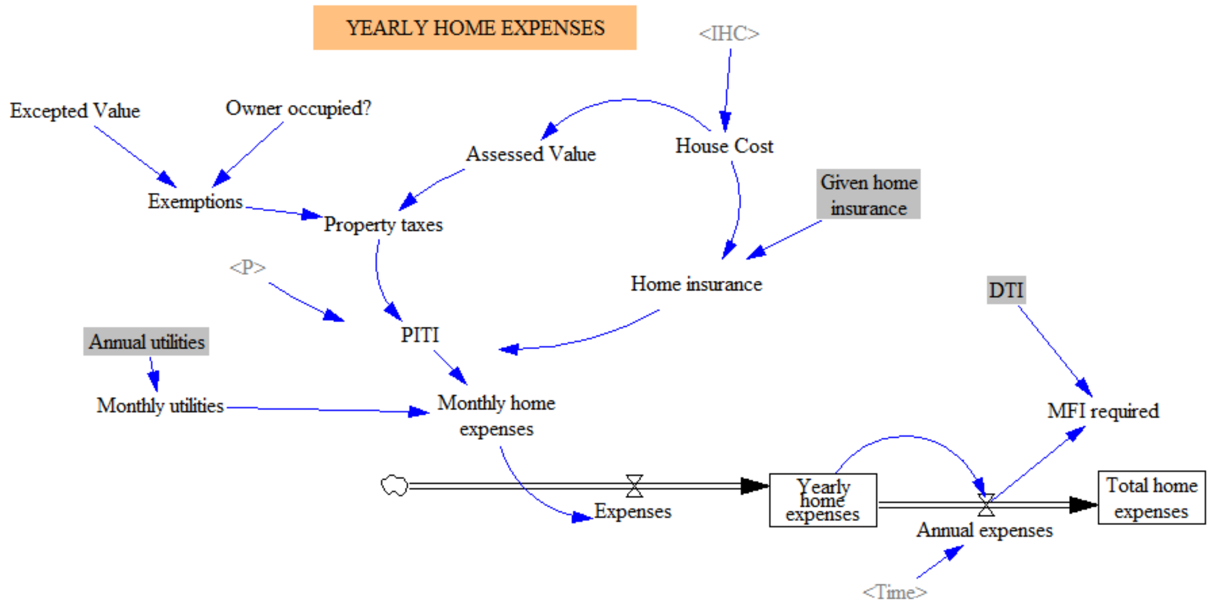


Figure 24. Proposed SD model for yearly home expenses

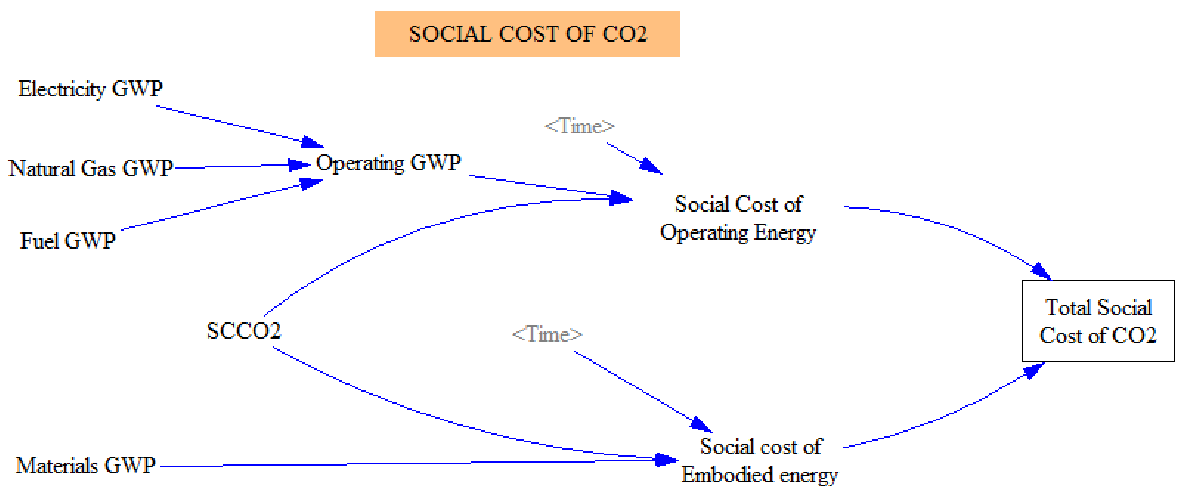


Figure 25. Proposed SD model for the social cost of carbon emissions

CHAPTER 6 MODEL DEVELOPMENT AND STRUCTURE

6.1 Model structure

The DSS guides the decision maker through the steps to select sustainable parameters during the early stages of the design process. Figure 26 presents a simplified version of the steps of DSS and the corresponding module associated with each step.

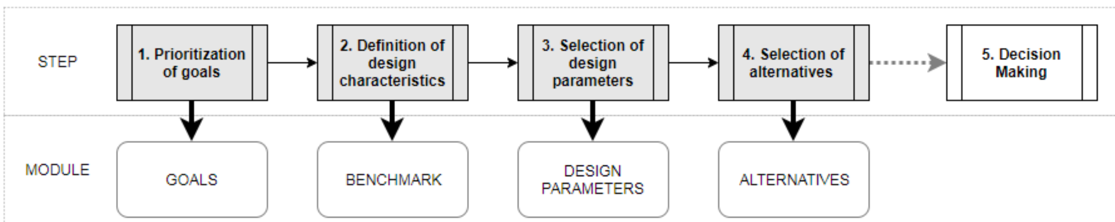


Figure 26. Steps and modules of the DSS

The first step is prioritizing design goals. In this step, the decision maker performs a pairwise comparison using the Goals module and establishes the weights of importance of the decision criteria. In the second step, the DM uses the Benchmark module to define the overall design characteristic. With this module, the decision maker explores costs associated with building size, family size, type of fuel for heating, and type of water consumption by using census data for the geographic region. The Benchmark module estimates the average cost of utilities and establishes the required minimum Median Family Income (MFI) using the financial information entered by the decision maker. The Benchmark module assists the decision maker to select the house size and define the target budget for the project.

The third step is the selection of parameters using the Design parameter module. The input information for this step is the result of a schematic design that defines aspects such as building location, size, orientation, and window to wall ratio (WWR). Simulations and calculations for the DSS follow the completion of this step by using data gathered from the first three system modules. The information flows through software interaction using Visual Basic, and the results are imported into the DSS to continue the process. The process outputs are cost, time, LCA, and alternative financial results. The Alternatives module contains the simulations and calculations results.

In the fourth step, which is the selection of alternatives, the decision maker requires at least two alternatives to make a selection in the Alternatives module. If more than two alternatives are available, the DM compares the two alternatives and makes a decision based on the AHP results. For future comparisons, the DSS stores alternative results.

The last step is decision making. The DM uses results from the Cost, Time, LCA, Financial, and Alternatives modules to select project parameters. If the DM is unsatisfied with the alternatives, the DM reiterates the process by changing parameters and creating new alternatives until reaching satisfactory results. Figure 27 shows the DSS modules, information flow, and task sequence.

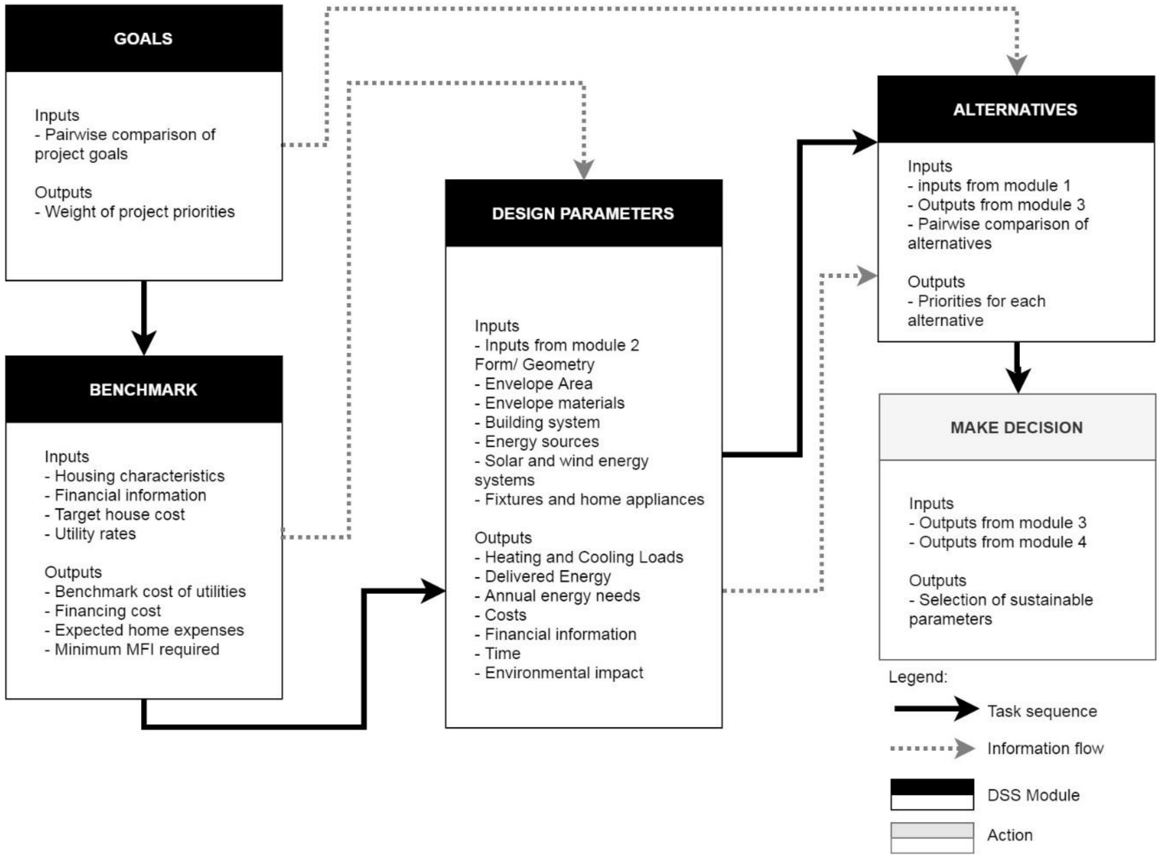


Figure 27. Information flow and task sequence of DSS modules

6.2 Architecture of the DSS

The interaction between the DM and the DSS occurs in a Microsoft Excel file called CPR.xls. The CPR file uses a group of auxiliary files and Visual Basic to exchange information, make calculations, and run the SD model. The Materials Database is built in the CPR file as well. Figure 28 represents the architecture of the DSS. The arrows show information flow and the interaction between the system and the decision maker.

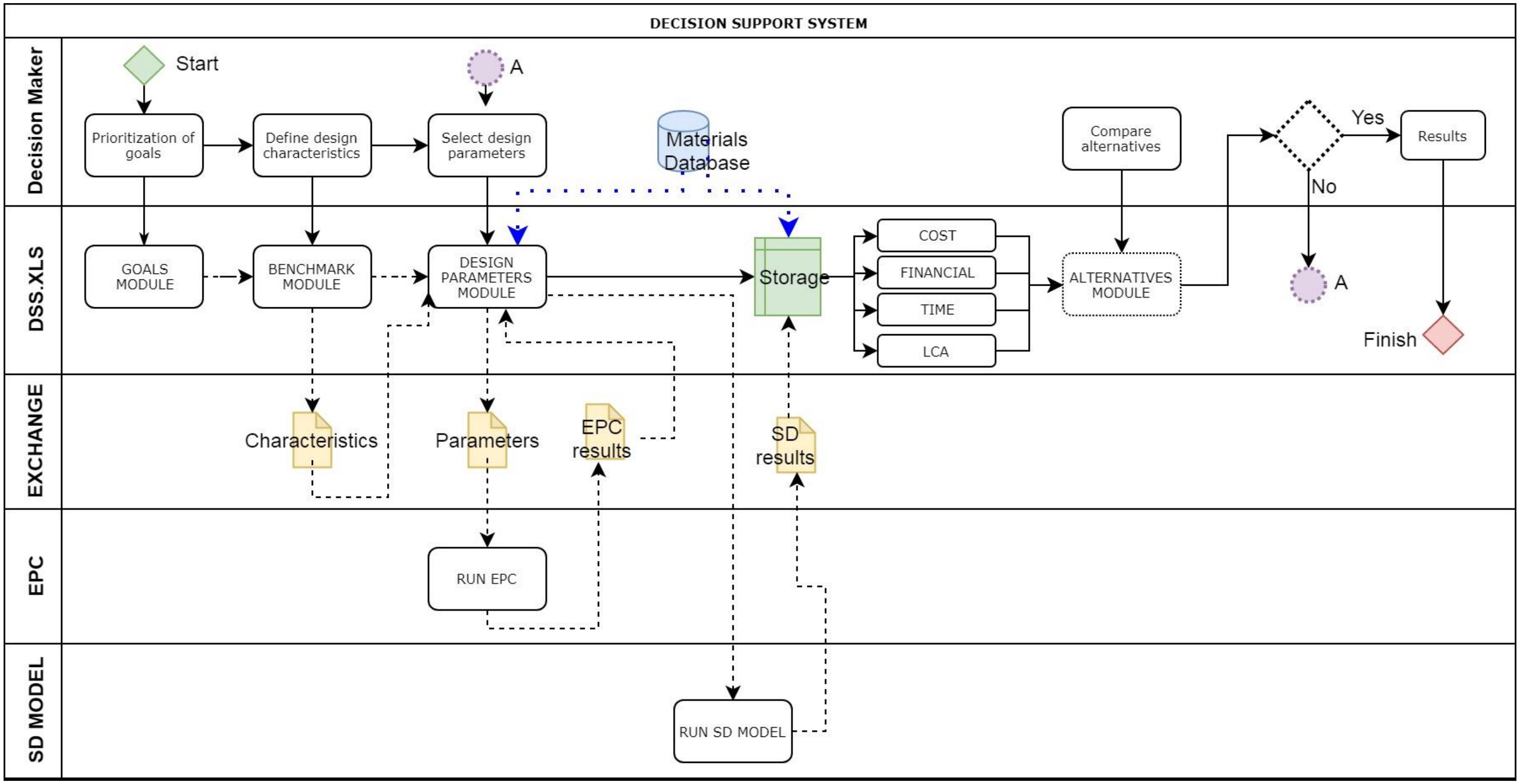


Figure 28. Architecture of DSS

The DSS works with an Excel-based building energy calculation tool developed by the Georgia Institute of Technology the Energy Performance Coefficient (EPC) calculator (J. H. Kim, 2016). The EPC is a reduced order building energy calculation tool that is widely adopted and recognized for large-scale building performance analysis. The EPC calculator uses normatively-defined modeling assumptions and parameters. This method is normative because it does not require modeling. Hence, modeler's bias is not introduced (J.-H. Kim, Augenbroe, & Suh, 2013). All input values in the model are fully defined and directly related to observable information in the design parameters module.

6.3 Case study

The case study house (CSH) selected for this study is a design from the 2015 U.S. Department of Energy (DOE) race to zero, a student design competition. The design corresponds to a two-story single-family house located in the downtown area of southeast Atlanta. The CSH was selected because the house type and location are in agreement with the scope of this research. Also, the information about the design goals and the resulting design are available on the DOE website, which facilitates comparing CSH and DSS results. Sustainability is the objective of the race to zero projects, and the information available includes the design parameters and design goals established by the team. For example, Figure 29 shows the goals established by the CSH design team.

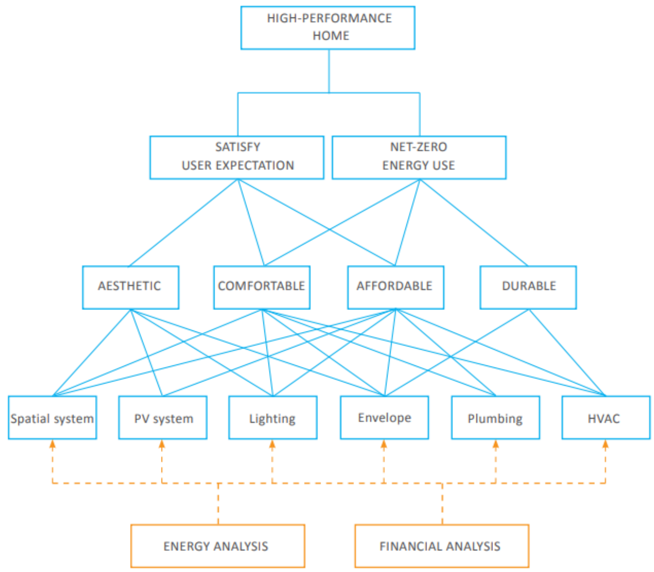


Figure 29. CSH goals (Source: Race to zero competition, 2015)

6.4 DSS modules

The menu of the DSS, displayed in Figure 30, leads the decision maker through the modules of the system in the order suggested by the DSS steps. The orange modules require user inputs, while the green modules are for calculation and simulation results. The explanation of DSS modules will use the CSH as an example.

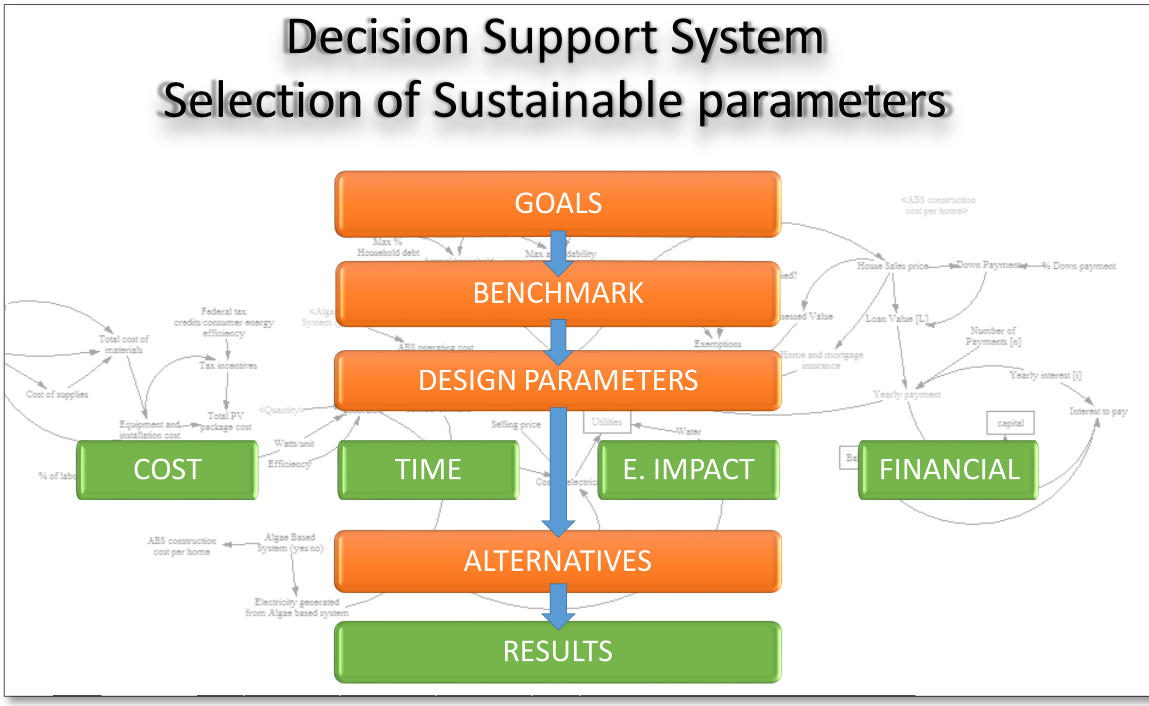


Figure 30. Menu of DSS

6.4.1 Goals module.

In the first step of the DSS, the decision maker evaluates goals in terms of their relative importance by performing a pairwise comparison between the goals. In the CSH case, the goals from the case study are interpreted and used as DSS input. As shown in Figure 31, the DM prioritizes goals using slide bars and the AHP that section 5.2.2 describes. The matrix shown in Table 14 uses the values obtained from the comparison. Also, the DSS assesses the consistency of the matrix. When the consistency ratio is smaller than 10%, the consistency is acceptable, and the screen displays the message, “Consistency is ok”; otherwise, the screen displays the message, “Revise your judgments”.

Figure 31. View of Goals module

Table 14. Pairwise comparison matrix for Case Study

Pairwise comparison matrix						
	n=	6	Ri	1.24		
	Affordability	Env. Impact	Aesthetics	Const. Duration	Energy efficiency	Water efficiency
Affordability	**1**	4.00	1.00	1.00	0.33	4.00
Env. Impact	0.25	**1**	0.25	1.00	0.33	1.00
Aesthetics	1.00	4.00	**1**	1.00	0.33	4.00
Const. Duration	1.00	1.00	1.00	**1**	0.33	4.00
Energy efficiency	3.00	3.00	3.00	3.00	**1**	4.00
Water efficiency	0.25	1.00	0.25	0.25	0.25	**1**

The DSS calculates the weights of the individual criteria. First, a normalized comparison matrix is created by dividing each value of the first matrix by the sum of its column, and then the criteria weight vector is obtained by averaging across the rows of the normalized matrix. These weights are normalized; therefore, their sum is 1. Table 15 presents the resulting normalized matrix.

Table 15. Normalized pairwise comparison matrix for Case Study

PRIORITIES							
	Normalized pairwise comparison matrix						Criteria weight vector
	Affordability	Env. Impact	Aesthetics	Const. Duration	Energy efficiency	Water efficiency	
Affordability	0.154	0.286	0.154	0.138	0.129	0.222	0.1804
Env. Impact	0.038	0.071	0.038	0.138	0.129	0.056	0.0785
Aesthetics	0.154	0.286	0.154	0.138	0.129	0.222	0.1804
Const. Duration	0.154	0.071	0.154	0.138	0.129	0.222	0.1447
Energy efficiency	0.462	0.214	0.462	0.414	0.387	0.222	0.3601
Water efficiency	0.038	0.071	0.038	0.034	0.097	0.056	0.0559

The weights from the criteria vector indicate the preferences of the DM among the goals. As seen in Table 16, the top priority for the CSH is energy efficiency, while the construction duration, aesthetics, durability, and affordability share the same importance. In contrast, water efficiency is the least important goal defined by decision makers.

Table 16. Priorities for Case Study House (CSH)

RANK	PRIORITIES	PERCENTAGE
1	Energy efficiency	**36.01%**
2	Aesthetics	**18.04%**
3	Affordability	**18.04%**
4	Const. Duration	**14.47%**
5	Env. Impact	**7.85%**
6	Water efficiency	**5.59%**

6.4.2 Benchmark module.

After selecting goals, the next step is defining benchmark characteristics. The DM has the option of selecting defining characteristics and obtaining the Medium Family Income required for a target house cost. The inputs and outputs of the Benchmark module fall into three groups: utilities, financial, and water rates. Figure 32 presents a general view of the Benchmark module. The cells in gray require input from the user, while the green cells represent results from the module.

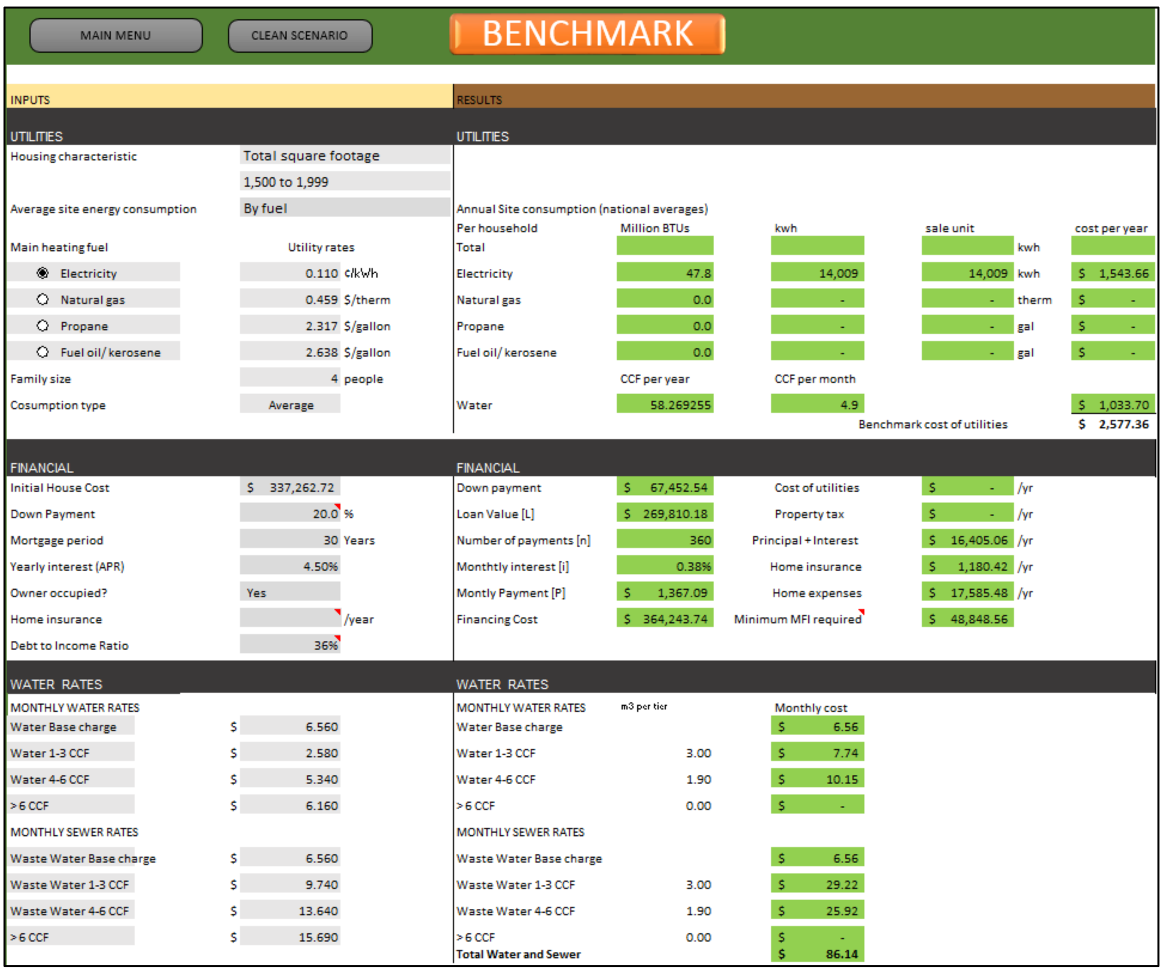


Figure 32. Benchmark module

The utility group uses the average values from the annual household site fuel consumption in the US sourced from the Residential Energy Consumption Survey (RECS), which the U.S. Energy Information Administration administers (EIA, 2016). The DM selects housing characteristics, type of site energy consumption, main heating fuel, and water use (i.e., high, average, or low). The utility group requires information about utility rates per fuel and the family size for water consumption.

The housing characteristics from the dropdown menu on the utility group fall into five categories. The DM selects one of the five categories (e.g., census classification, climate region, housing type, total square footage, number of household members) and the corresponding subcategory that best describes the characteristics of the unit subject to modeling. Figure 33 depicts a schematic diagram of the housing characteristics for the utility group. The DSS uses information from the Residential Energy Consumption Survey (EIA, 2016) and utility rates provided by the user to estimate the benchmark cost of energy for the CSH. This benchmark informs the DM about the expected costs of utilities using national averages and establishes a reference point for comparison.

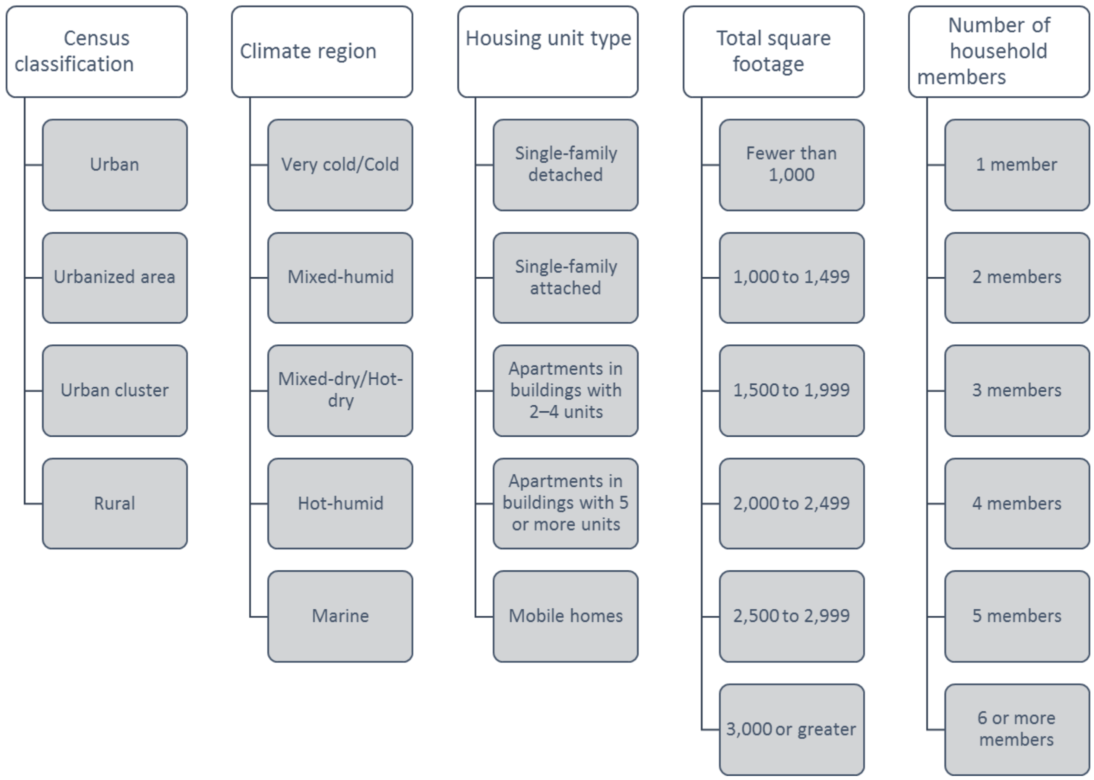


Figure 33. Housing characteristics for the utility group.

The financial group collects information about the expected budget for the project and the financial information of the homeowner. This group is useful to define a target cost for the project and gives information about the financial parameters. The results also consider the cost of utilities and other home expenses to calculate the minimum Median Family Income (MFI).

The last group of the benchmark module is the water rates group, which is the module used by the DM to give information about the cost per tier of 100 cubic feet (CCF). The total cost of water and sewer from the results of this module connect to the previous two groups of the benchmark module.

6.4.3 Design parameters module

The third step is the selection of design parameters for the building. The design parameters module incorporates seven groups, as shown in Figure 34 and Figure 35. The first two groups gather information about the geometric characteristics of the design. The DM introduces the information about the form/geometry and envelope area of the model in imperial units. The third group is the envelope materials. In this group, the DM selects the envelope materials by using a dropdown menu. A database, which connects with other parts of the DSS, stores the properties of the materials. Thus, the amount of information that the DM needs to gather decreases, as well as the time to create each alternative. For example, the DM selects the material for the roof plane, attic floor, and roof sheathing; the DSS gathers from the database the corresponding u-value, absorption coefficient, and emissivity. The building system group, energy sources group, the solar and energy systems group, and the fixtures and home appliances group also work with dropdowns lists that retrieve information from the materials database.

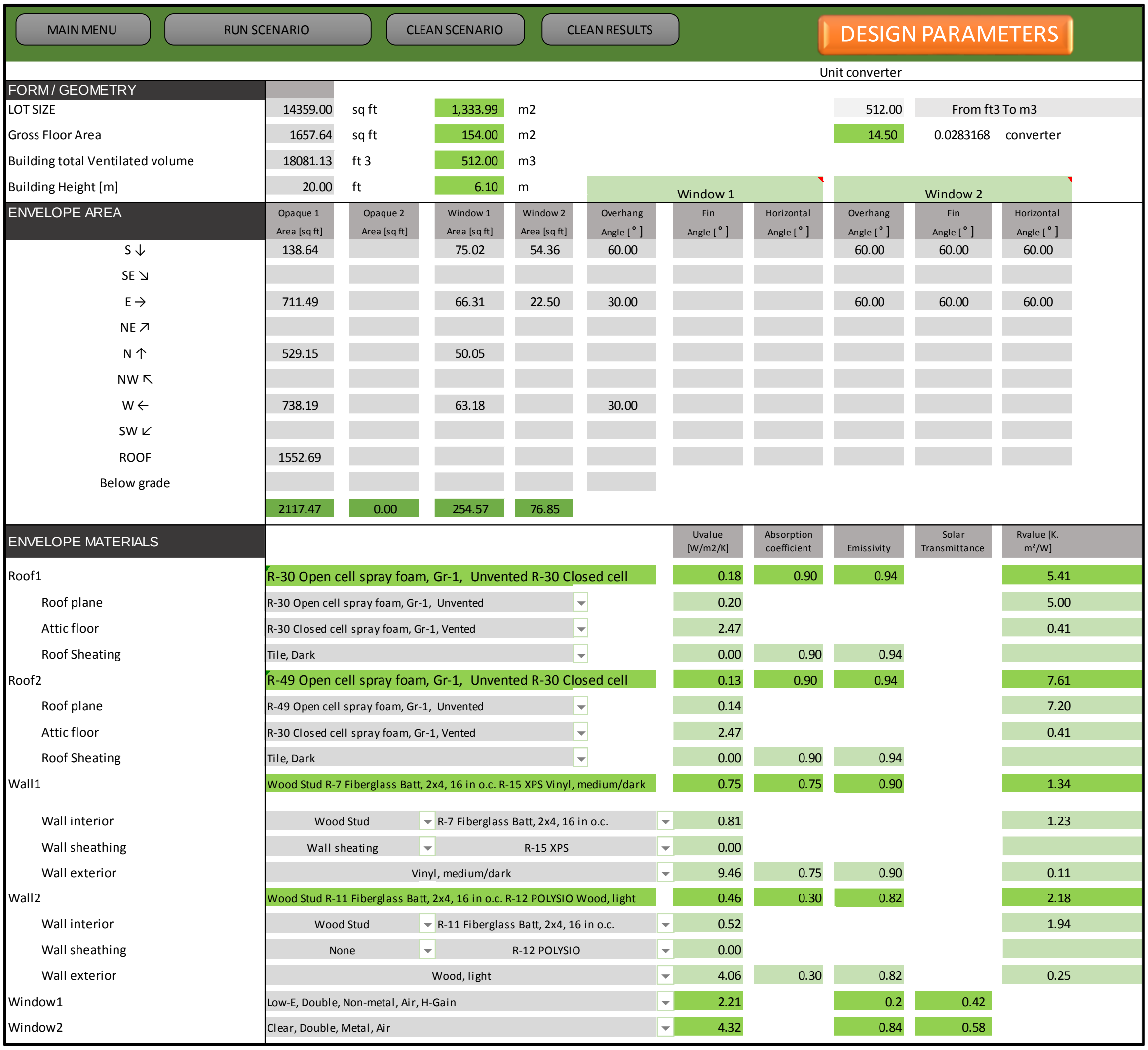


Figure 34. Design parameters module (Groups 1-3)

BUILDING SYSTEM	(System / Heat distrition by / Cold distribution by / room temp. cntrl)								
HVAC system type:	37. Direct expansion single split system including variable refrigerant fl								
Ventilation and Cooling type	1. Mechanical system only; no provision for natural ventilation								
Heat recovery type	Two-element system (0.6)								
Exhaust air recirculation percentage	No exhaust air recirculation								
Building air leakage level	Low	(Air flow m3/h per floor area at 04Pa)→						0.9	
Pump control for cooling	No pump for cooling								
Pump control for heating	No pump for heating								
DHW Distribution System	All Taps Within 3m from Heat Generation								
DHW Generation System	Electric (0.75)								
Building Energy Management System	1	No building automation function							
ENERGY SOURCES									
Primary energy source for Heating	Electricity								
Primary energy source for DHW	Electricity								
Primary energy source for Cooling	Electricity								
SOLAR AND WIND ENERGY SYSTEMS									
PHOTOVOLTAIC SYSTEM	YES/NOT								
PV module Surface Area (sq ft)	64.58	sq ft	6.00	m2	Pv Panel	olar PV Panels x 18 (SunviaOPT280-60-4-10(			
PV Module Orientation	S								
PV Module Angle (tilt in degrees)	30								
Type of photovoltaic module	Mono crystalline silicona	PV panel peak power coefficient (kW/m2)				0.15			
Type of building integration of the PV module	Strongly ventilated of forcec	PV system performance factor (level of ventilation)				0.80			
PV compensation	Feed-in Tariff								
SOLAR WATER HEATING SYSTEM	YES/NOT								
Solar Collector Surface Area (sq ft)	64.58	sq ft	6.00	m2	Solar Panel	Solar Water Heater Product #: RS80-40BP			
SHW module orientation	S								
SHW module angle (tilt in degrees)	30								
WIND TURBINE SYSTEM	YES/NOT								
Wind Turbine diameter [m]	0.00		0.00	m					
Wind Turbine efficiency	0.40								
FIXTURES AND HOME APPLIANCES									
Family size	4.00								
Full bathrooms	2.00	Half bathrooms	2.00						
Toilets	Glacier Bay N2430RB-HD / N2430T-SF-HD					1.28	gpf	35.38	m3 per year
Shower fixture	Niagara "N2917"					1.75	gpm	48.37	m3 per year
Lavatory Faucets	Glacier Bay Aragon HD67090W-5A"					1.2	gpm	53.06	m3 per year
Clothes Washer	Maytag 2310409					6698.00	gpy	25.35	m3 per year
Dishwasher	Whirlpool WDF330PAH"					3.50	gpl	3.45	m3 per year

Figure 35. Design parameters module (Groups 4-7)

Through the "run scenario" option, the information from the groups flows from the EPC calculator and the SD model. Calculations and simulation occur in the background, and a copy of the results goes to the CPR file. The DM does not have to interact with the EPC Calculator, or the SD model to obtain the results. Thus, the process for the DM is simplified because knowledge about the applications mentioned above is unnecessary. Nevertheless, an advanced user has access to greater capabilities of the EPC calculator.

As shown in Figure 36, the module displays the results from the EPC calculator. APPENDIX C shows the Visual Basic codes to run the simulations.

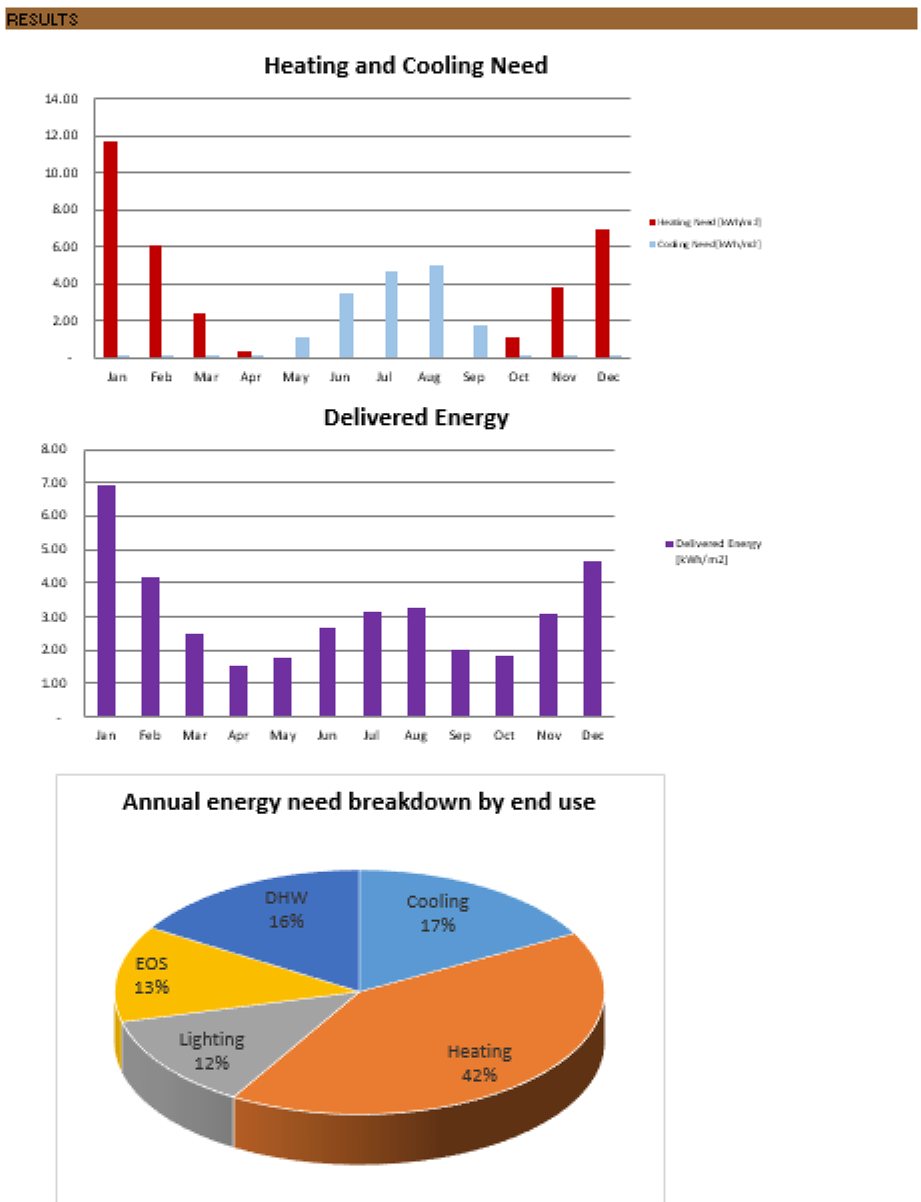


Figure 36. Heating need, cooling need, delivered energy, and annual energy breakdown by end use.

6.4.4 Cost, time, environmental impact, and financial modules

Following the third step of the process, four modules store the simulation and calculation results. The modules display different information per the designation given by the type of module. These modules contain information from the calculations and simulations of previous modules. The cost, time, environmental impact, and financial modules provide the decision maker with relevant information and show details that facilitate comprehending the results.

The first is the cost module. This module presents an estimate of the cost for the project using the UniFormat method. UniFormat is most notably used for estimators to present cost estimates during the schematic design because the method arranges the construction information based on functional elements. The cost estimate presented in the DSS is a combination of two methodologies for cost estimates: cost per square foot and unit costs. The cost per square foot uses the area of the lot and the area of the housing along with the most recent data obtained from the construction cost survey of the National Association of Home Builders (NAHB) to estimate the cost per square foot of the parametric components that are not defined at the early stage of the project. The unit cost results from the quantities provided in the design parameters module and the costs per unit acquired from RS MEANS and form local suppliers of materials (i.e., Lowes and Homedepot). The costs are stored in the material database and are used by the DSS to calculate the unit cost. Figure 37 shows a summarized version of the results from the cost module.

MAIN MENU

COST

Single Family Price and Cost Breakdowns							
	Average Lot Size:	14,359	sq ft			Alt1 Lot Size:	14,359.00
	Average Finished Area	2,607	sq ft			Alt1 Finished Area:	1,657.64
I. Sale Price Breakdown	**Average**	**Share of Price**		**Cost per S.F. living area**	**Total Cost**		**ALTERNATIVE**
A. Finished Lot Cost	$74,509	18.60%	$ 5.19			35.00%	$ 74,509.00
B. Total Construction Cost	$246,453	61.70%					$ 187,988.55
C. Financing Cost	$5,479	1.40%	1.71%				$ 4,480.98
D. Overhead and General Expenses	$17,340	4.30%	5.40%				$ 14,181.45
E. Marketing Cost	$4,260	1.10%	1.33%				$ 3,484.02
F. Sales Commission	$14,235	3.60%	4.44%				$ 11,642.04
G. Contractor's overhead and profit and plans.	$37,255	9.30%	11.61%				$ 30,468.86
Total Sales Price	**$399,532**	**100%**					**$ 326,754.91**
II. Construction Cost Breakdown	**Average**	**Share of Construction**		**unit**	**quantity**	**unit cost**	**subtotal**
I. Site Work (sum of A to E)	$16,824	6.80%	$ 6.45				$ 10,708.35
II. Foundations (sum of F to G)	$23,401	9.50%	$ 8.98				$ 14,869.03
III. Framing (sum of H to L)	**$47,035**	**19.10%**	**$ 18.04**				**$ 30,588.35**
IV. Exterior Finishes (sum of M to P)	**$35,474**	**14.40%**	**$ 13.61**				**$ 25,139.48**
V. Major Systems Rough-ins (sum of Q to T)	**$32,959**	**13.40%**	**$ 12.64**				**$ 23,018.41**
VI. Interior Finishes (sum of U to AE)	**$72,241**	**29.30%**	**$ 27.71**				**$ 58,385.11**
VII. Final Steps (sum of AF to AJ)	**$16,254**	**6.60%**	**$ 6.23**				**$ 10,327.10**
VIII. Other	**$2,265**	**0.90%**	**$ 0.87**				**$ 14,613.92**
Total Construction cost							**$ 187,988.55**

Figure 37. Cost module

Given that DSS uses information from an early stage of design, the cost estimated in this module is equivalent to that of an estimate class 4 with an expected accuracy between -20% and + 30% based on the cost estimate classification system of Association for the Advancement of Cost Engineering (AACE), as seen in Table 17 and Figure 38.

Table 17. Cost estimate classification matrix for building and general construction industries.

Estimate class	**Maturity level of Project definition**	**End usage**	**Methodology Typical estimating method**	**Expected accuracy range***
Class 5	0% to 2%	Functional area, or concept screening	SF o m2, parametric models, judgement or analogy	L: -20% to -30% H: +30% to +50%
Class 4	1% to 15%	Schematic design or concept study	Parametric models, assembly driven models	L: -10% to -20% H: +20% to +30%
Class 3	10% to 40%	Design development, Budget authorization, feasibility	Semi-detailed unit cost wit assembly level line ítems	L: -5% to -15% H: +10% to +20%
Class 2	30% to 75%	Controled unit costs with forced detailed take-offs	Detailed unit cost with forced detailed take-off	L: -5% to -10% H: +5% to +15%
Class 1	65% to 100%	Check estimate or pre-tender, change order	Detailed unit cost with detailed take-off	L: -3% to -5% H: +3% to +10%

* Typical variation in low and high ranges at an 80% confidence interval

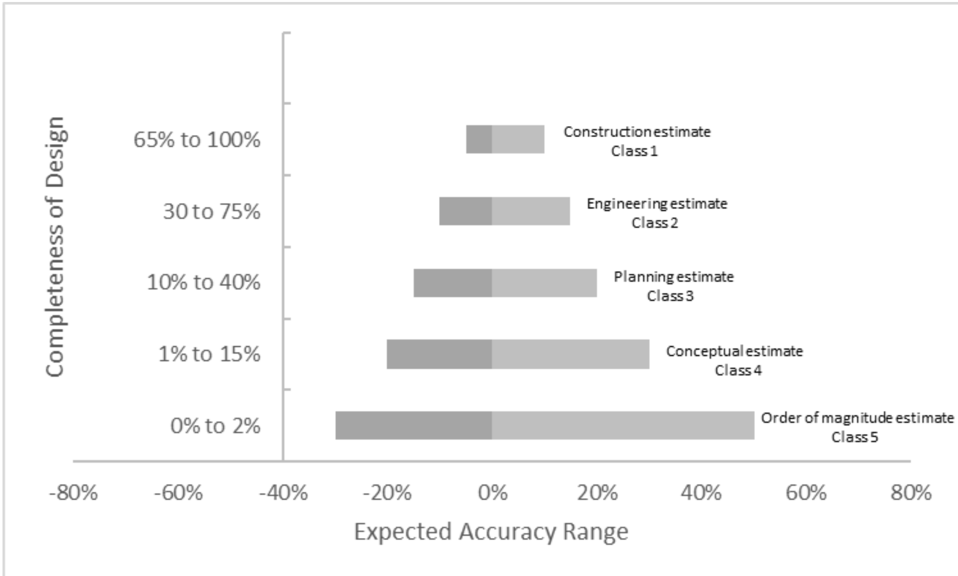


Figure 38. Cost estimate classification for building and general construction industries

The time module is also a module that estimates the days required for the construction of the project using the Work Breakdowns Structure (WBS) and the quantities taken from the design parameters. The time module estimates the activity duration using a combination of analogous estimating and parametric estimating. Similar to the cost module, the schedule of this module is equivalent to a class 4 estimate with an expected accuracy between -20% and +30% given that the project is at an early stage and less than 15% of the project is defined. The time module presents the project duration with a Gantt chart that summarizes the duration of the group elements and the total construction time, as seen in Figure 39.

The estimation of house construction duration may have minimal variations between alternatives because in most cases, two parameters share the same duration in the construction process. For example, changing the type of glazing in a window has a notable influence over the cost, environmental impact, and energy consumption of the house. Nevertheless, the construction duration will remain the same; the installation process takes the same time because it does not depend on the glazing material but the geometric characteristics of the window. Nevertheless, other variations, like changing the wall interior from wood studs to concrete masonry units (CMU), will have a bigger impact on project duration.

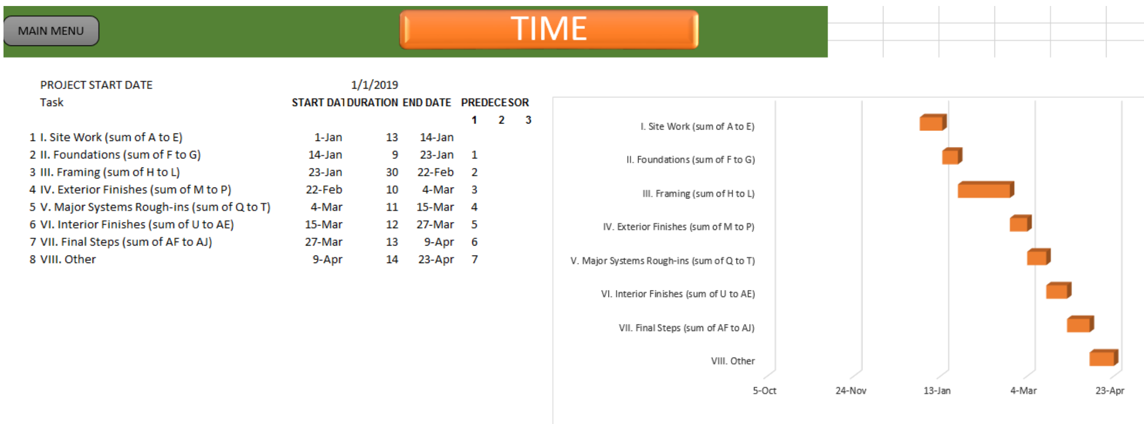
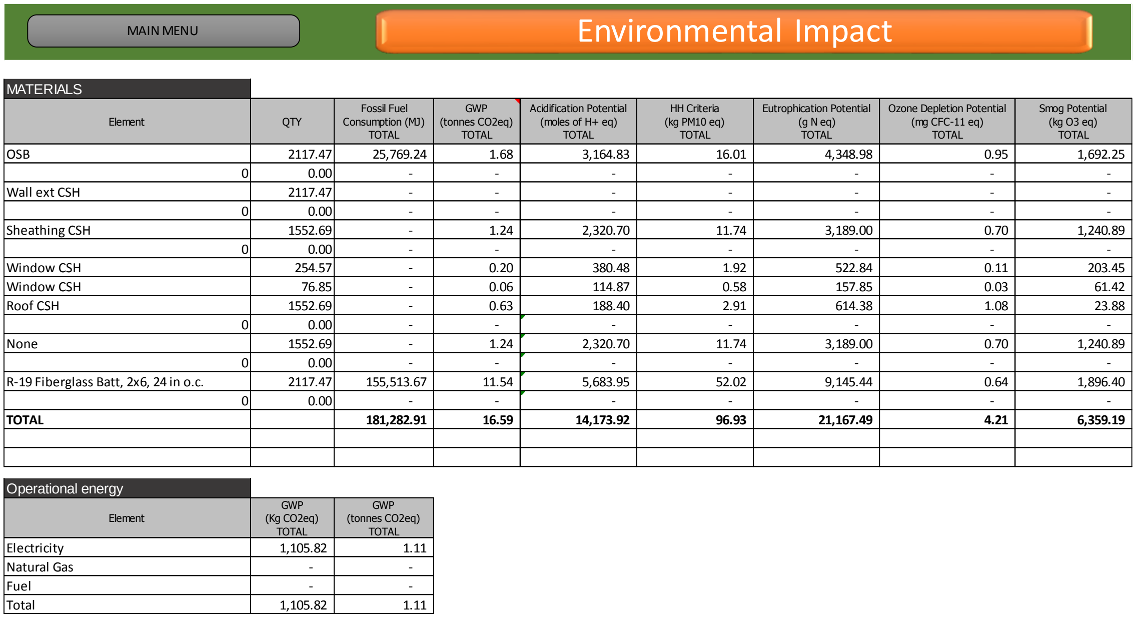


Figure 39. Time module

The environmental impact module, shown in Figure 40, measures the effects produced by the construction and operation of the building. First, eight categories are used to quantify the impact of the construction materials: fossil fuel consumption, global warming potential (GWP), acidification potential, human health criteria, aquatic eutrophication potential, ozone depletion potential, and smog potential. The construction impact uses information from the database developed by the National Renewable Energy Laboratory (NREL) (National Renewable Energy Laboratory, 2012), available through the Athena EcoCalculator for Residential Assemblies. The values obtained for the materials only account for the impacts of the raw material extraction, manufacturing, use, and end-of-life, but it does not measure or account for operational energy.

The GWP of the fuels required to delivered energy to the building (i.e., CO2 emissions) measures the environmental impact produced by the operational energy of the building. Consequently, GWP measures the environmental impact for the alternative, as the sum of the environmental impact of the operating energy and the embodied energy.

"Social cost of carbon" (SC-CO2) is a measure, in dollars, for the future damages done by a ton of carbon dioxide (CO2) emissions in a particular year (Newbold, Griffiths, Moore, Wolverton, & Kopits, 2010). The SC-CO2 is meant to be a comprehensive estimate of climate change damages and includes changes in net agricultural productivity, human health, property damages from increased flood risk, and changes in energy system costs, such as reduced costs for heating and increased costs for air conditioning. The current estimates of the SC-CO2 are useful measures to assess the climate impacts of CO2 emission changes (Interagency Working Group on Social Cost of Carbon, 2010) and used in the DSS to quantify the environmental impact of the alternatives.



MAIN MENU

Environmental Impact

MATERIALS

Element		QTY	Fossil Fuel Consumption (MJ) TOTAL	GWP (tonnes CO2eq) TOTAL	Acidification Potential (moles of H+ eq) TOTAL	HH Criteria (kg PM10 eq) TOTAL	Eutrophication Potential (g N eq) TOTAL	Ozone Depletion Potential (mg CFC-11 eq) TOTAL	Smog Potential (kg O3 eq) TOTAL
OSB		2117.47	25,769.24	1.68	3,164.83	16.01	4,348.98	0.95	1,692.25
	0	0.00	-	-	-	-	-	-	-
Wall ext CSH		2117.47	-	-	-	-	-	-	-
	0	0.00	-	-	-	-	-	-	-
Sheathing CSH		1552.69	-	1.24	2,320.70	11.74	3,189.00	0.70	1,240.89
	0	0.00	-	-	-	-	-	-	-
Window CSH		254.57	-	0.20	380.48	1.92	522.84	0.11	203.45
Window CSH		76.85	-	0.06	114.87	0.58	157.85	0.03	61.42
Roof CSH		1552.69	-	0.63	188.40	2.91	614.38	1.08	23.88
	0	0.00	-	-	-	-	-	-	-
None		1552.69	-	1.24	2,320.70	11.74	3,189.00	0.70	1,240.89
	0	0.00	-	-	-	-	-	-	-
R-19 Fiberglass Batt, 2x6, 24 in o.c.		2117.47	155,513.67	11.54	5,683.95	52.02	9,145.44	0.64	1,896.40
	0	0.00	-	-	-	-	-	-	-
TOTAL			**181,282.91**	**16.59**	**14,173.92**	**96.93**	**21,167.49**	**4.21**	**6,359.19**

Operational energy

Element	GWP (Kg CO2eq) TOTAL	GWP (tonnes CO2eq) TOTAL
Electricity	1,105.82	1.11
Natural Gas	-	-
Fuel	-	-
Total	1,105.82	1.11

Figure 40. Environmental impact module

The cost, time, and environmental impact modules are an approximate of the final cost, construction duration, and life cycle assessment of the building. Although the accuracy of the results at this early stage cannot be greater because the project is not entirely defined, the results are useful for making comparisons among alternatives and selecting the alternative that better meets the goals established by the decision maker.

The last module from the group of results is the financial module, shown in Figure 41. This module uses the outputs from the simulations and calculations and displays the financing cost, annual utilities, and the MFI of the alternative. The difference between this module and the Benchmark module is that the benchmark uses national averages to make a first estimating of the results, while the financial module uses the results from the selected alternatives to calculate the financial cost from the alternative.

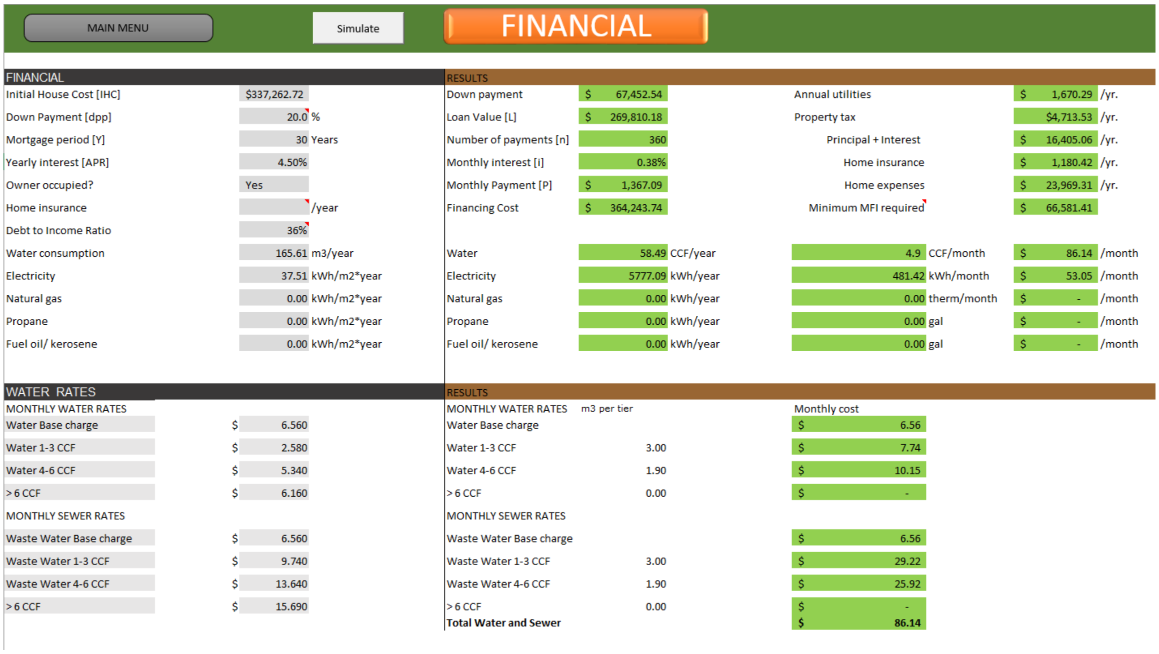


Figure 41. Financial module

6.4.5 Alternatives module

The fourth step is the selection of alternatives. The alternatives module presents a summary of the results obtained from the current set of parameter. The DSS can save the alternative's results for comparison with other alternatives. The comparison of the alternatives uses the weights obtained from the AHP and the results from the DSS to obtain the priorities for the alternatives. The priorities represent the relative ability of the alternative to achieve the decision goal. For example, in Figure 42 the house option 3 has a higher ability (52%) to achieve the goals of the decision maker compared with the alternative "basic house design for Atlanta" (48%). Consequently, the house option 3 is the best alternative. The alternatives module makes a comparison between the alternatives that are selected using the numerical values obtained from the DSS to calculate their numerical weight or priority. Aesthetics is the only criteria that require a pairwise comparison from the decision maker. The aesthetics of an alternative is subjective to the preferences of the decision maker and requires to consider the composition of the alternative with all its elements. Individually assigning values to the parameters is ineffective because the aesthetics of the two elements are different if subject to individual evaluation or if combined into one alternative. For example, a roof sheeting, a wall sheeting and a certain type of window can receive the highest value if compared to other elements of their group of materials, but if combined into one alternative, the resulting combination of materials might not be the most appealing solution for the decision maker.

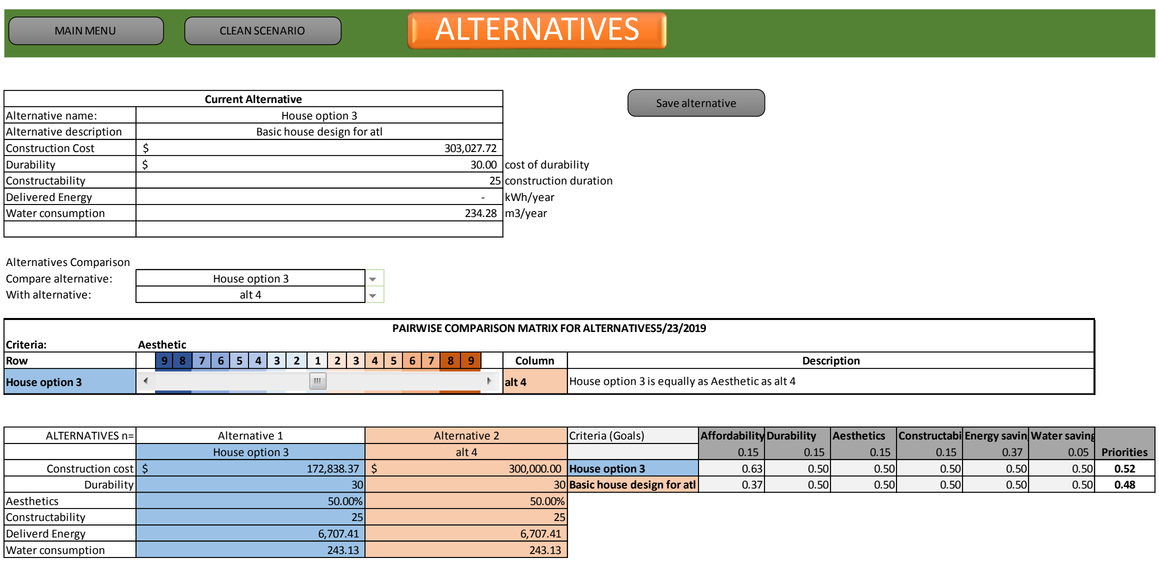


Figure 42. Alternatives module

Finally, the last step is the selection of the alternatives. The decision maker continues with the exploration of combinations, and the process continues creating new alternatives and making comparisons until the decision maker finds the alternative that better satisfies the criteria for the goals formulated in the first step of the process. Then the decision maker establishes the parameters that will be incorporated in the delivery process using the selected alternatives.

CHAPTER 7 MODEL RESULTS AND DISCUSSION

7.1 Model validation

The proposed model was validated using the tests of model structure and model behavior that Figure 43 shows (Senge & Forrester, 1980). The validation of the model structure consists of five tests. The structure of the model was proposed from the literature and validated through the interviews with experts. The verification of model assumptions and the knowledge of experts about the structure of the real process of design and selection of parameters reviewed the structure. In this sense, the model boundary-adequacy test underwent testing with experts as the model aggregation, exploring the inclusion of all relevant structure required for the system. Also, the parameters used in the model underwent verification with the literature from existing information published by U.S. government agencies and programs (EIA, 2016; Energy Star, 2018; National Renewable Energy Laboratory, 2018), and from private sources of information (Home Depot, 2019; R. S. Means Company, 2017; R.S. Means Company, 2017).

The dimensional consistency test was conducted through the development of the DSS and particularly with the SD model using the option verification of units available in the system dynamics software. The extreme condition took place during the development of the DSS. After completing the system, the verification took place with the construction of alternatives with extreme input values.

On the other hand, three tests of model behavior were used to validate the DSS. First, the system underwent verification for reasonable behavior over a different range of input values. During the system construction, the behavior-anomaly test was used extensively to detect errors in the equations of the SD model, which occurred especially with equations involving stocks and flows. An example is when the formula underwent annual calculation, and the results were out of the expected range because the formula was computing monthly values. Finally, the other two tests are the behavior-prediction test, which focuses on future or expected behavior, and the behavior-reproduction test, which focuses on reproducing historical behavior. Manual calculations and verification of expected values and results from the case study were used to verify these two types of tests.

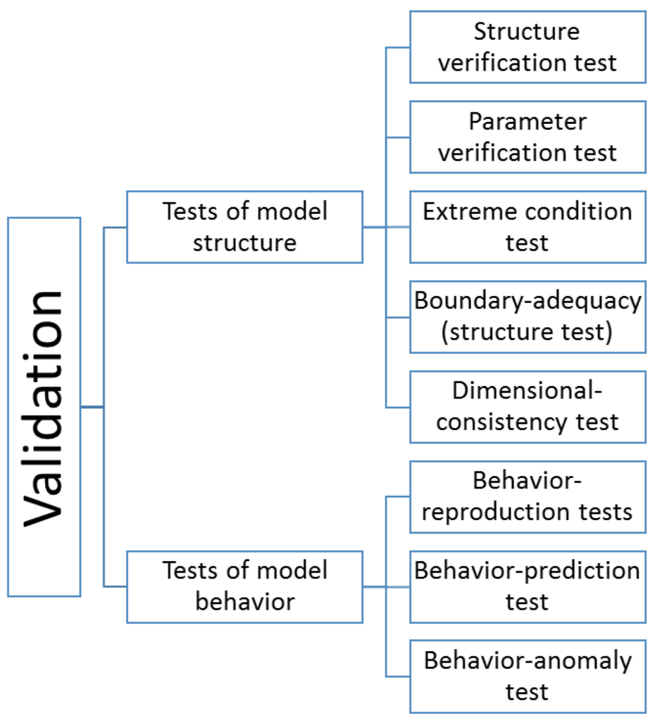


Figure 43. Tests used for model validation

7.2 Creation of alternatives

The DSS was used to create alternatives for the CSH. Table 18 summarizes the data from the case study. The first alternative, ALT 1, corresponds to the final design to implement for the CSH. ALT 1 is a two-story single-family house with a gross floor area of 18,081 square feet. The CSH was designed for mixed humid climate of Atlanta using existing materials and systems. The CSH is a net zero energy house when using PV panels and solar water heater. Other alternatives were created using the CSH as a baseline. Table 19 shows the description of the alternatives and Table 21 shows the results for each alternative.

Table 18. General data for case study

Parameter	CSH (ALT 1)
Lot size	14,359 sqft
Gross Floor Area	1,657 sqft
Building total Ventilated volume	18,081 ft 3
Building Height [m]	16.40 ft
Walls	2x6 wood frame; fiberglass cavity batt R-19; 0.5" XPS board R-3; total R-22
Roof	2x10 rafters; fiberglass cavity batt R-30; 1.25" ccSPF R-8.75; 0.5" XPS board R-3; total R-41.75
Windows	Double-paned vinyl-frame, U=0.27, SHGC=0.18
HVAC system type	Direct expansion single split system including variable refrigerant flow systems
Energy sources	Electricity
PV system	Total area 313.88 sq ft; orientation =south; PV module angle=30
Solar water heating system	Area= 64.58 sq ft; module orientation=south; nodule angle=30

The case study house, named ALT 1, was used as a baseline to create the other alternatives. The alternative ALT2 uses the same parameters of ALT1, including the solar collector but without PV panels. Alternative ALT3 preserves the construction specifications of CSH but doesn't include PV panels or solar collector. The construction cost of ALT 2 is lower than ALT 1 while the SCCO2 and the delivered energy are higher for ALT2 than for ALT1. These results are consistent with expectations from the modification of the alternative. Given that PV panels and solar collector have a great impact on the delivered energy of the alternative and the construction cost, the alternatives explored different combinations modifying these two parameters. Alternatives ALT 5 and ALT 6 explore the use of different sizes of PV panels for the CSH. To test the system for extreme conditions, the ALT 7 and ALT8 were created using a combination of materials with low R-values for the walls and roof and with windows with a high U value compared with ALT1. The general data for the last two alternatives is shown in Table 20.

Table 19. Description of alternatives for CSH.

Alternative name:	Alternative description	Construction cost [Dollars]
ALT 1	CSH final design WITH 304 sq ft pv panels + 64.58 sq ft solar collector	$ 187,988.55
ALT 2	CSH no PV panels +solar collector	$ 180,753.07
ALT 3	CSH no PV panels - no solar collector	$ 173,374.63
ALT 4	CSH 304 sq ft PV panels - no solar collector	$ 180,384.15
ALT 5	CSH 208 sq ft PV panels + solar 64.58 sq ft collector	$ 185,549.05
ALT 6	CSH 2304 sq ft PV panels + solar 64.58 sq ft collector	$ 187,762.59
ALT 7	Change envelope mat + 304 sq ft PV + 64.58 sq ft solar collector	$ 171,987.62
ALT 8	Change envelope mat + 2200 sq ft PV + 64.58 sq ft solar collector	$ 215,704.88

Table 20. General data for Alternatives ALT7 and ALT8.

Parameter	
Walls	Wood Stud Uninsulated, 2x4, 16 in o.c. OSB, R-10 XPS Aluminum, medium/dark, Total R-0.11
Roof	R-19 Fiberglass Batt, Gr-1, Unvented Uninsulated, vented Metal, Dark, Total R-3.9
Windows	Clear, Double, Metal, Air, U=4.32
HVAC system type	Direct expansion single split system including variable refrigerant flow systems
Energy sources	Electricity
Solar water heating system	Area= 64.58 sq ft; module orientation=south; nodule angle=30

7.3 Analysis and results

Different alternatives were created with the aim of observing the effectiveness of the model in estimating the results for the alternatives. The cost and construction duration of the alternatives are summarized in Table 21. The construction cost is the direct cost of materials and labor required to build the project. The construction cost is different to the sales price, which is available on the cost module and includes the cost of the land, the financing cost, and the contractor's costs, overhead and profit. The social cost of the embodied energy is the social costs of the CO2 emissions caused by the production, transportation, or installation of materials related the construction of the project. The social cost of embodied energy of the PV panels and the solar collector is not included in the embodied energy because it is included in the social cost of the operational energy. The social cost of the operational energy is the cost of the CO2 emissions caused by the operational energy of the house for a 30 year period. The construction duration is the time in months required to build the house and install the systems. Finally, the costs of delivered energy and water consumption is the cost of the utilities required to operate the house for a 30 year period.

The results obtained from the model show a reasonable behavior compared with the expected results from the alternatives. The alternative with the lower construction cost was ALT 7. The construction cost of ALT 7 is $ 16,000.93 lower than the construction cost of ALT 1. Both alternatives use PV panels, but given the difference in the envelope materials ALT 7 requires 45,463 Kwh/year of energy to compensate for the energy loses from the envelope. The additional energy cost for ALT 7 is $150,295.32 dollars for 30 year period ($5,009.84 per year), meaning that the payback period for the materials in ALT 1 is only 3.9 years compared with the materials of ALT 7. This result shows that an investment of $ 16,000 in better materials will save $150,295 dollars over a 30 year period. In addition to this, the social cost of ALT 7 is $2,936 dollars higher that ALT 1. Selling electricity back to the grid was not an option for the house of the case study. For this reason, the social cost of operational energy and the delivered energy doesn't take into account the impact of the additional energy produced by the PV panels beyond the house needs.

Table 21. Costs and construction duration of alternatives for CSH

Alternative name:	Construction cost [Dollars]	Social cost of embodied energy [Dollars/ 30 year period]	Social cost of operational energy [Dollars/ 30 year period]	Construction duration [Months]	Delivered energy [Dollars/ 30 year period]	Water consumption [Dollars/ 30 year period]	Total cost [Dollars/ 30 year period]
ALT 1	$ 187,988.55	$ 685.12	$ -	11	$ -	$ 31,011.12	$ 219,684.79
ALT 2	$ 180,753.07	$ 685.12	$ 282.19	10	$ 14,444.99	$ 31,011.12	$ 227,176.48
ALT 3	$ 173,374.63	$ 685.12	$ 342.70	9	$ 17,542.38	$ 31,011.12	$ 222,955.95
ALT 4	$ 180,384.15	$ 685.12	$ -	10	$ -	$ 31,011.12	$ 212,080.39
ALT 5	$ 185,549.05	$ 685.12	$ -	11	$ -	$ 31,011.12	$ 217,245.30
ALT 6	$ 187,762.59	$ 685.12	$ -	11	$ -	$ 31,011.12	$ 219,458.83
ALT 7	$ 171,987.62	$ 675.34	$ 2,936.07	10	$ 150,295.32	$ 31,011.12	$ 356,905.48
ALT 8	$ 215,704.88	$ 675.34	$ 95.99	13	$ 4,913.43	$ 31,011.12	$ 252,400.76

To compare alternatives, the comparison of aesthetics is equally important. After comparing the alternatives and using the goals defined for the project, the best alternative was ALT 4. Table 22 depicts results from the comparison of alternatives. The priorities are obtained by multiplying the score matrix **S** with the priority vector **w**, previously obtained from equation (2) on chapter 5. The global score **v,** obtained from equation 4 is assigned by the AHP to each option is label as the priories in the comparison of alternatives

$$v = S \cdot w \qquad (4)$$

Table 22. Priorities from the comparison of alternatives.

Criteria (Goals)	Affordability	Env. Impact	Aesthetics	Const. Duration	Energy savings	Water savings	Priorities
	0.18	0.08	0.18	0.14	0.36	0.06	
ALT 1	0.49	0.50	0.33	0.48	0.69	0.50	**0.53**
ALT 2	0.51	0.50	0.67	0.52	0.31	0.50	**0.47**

Criteria (Goals)	Affordability	Env. Impact	Aesthetics	Const. Duration	Energy savings	Water savings	Priorities
	0.18	0.08	0.18	0.14	0.36	0.06	
ALT 1	0.48	0.50	0.25	0.45	0.69	0.50	**0.51**
ALT 3	0.52	0.50	0.75	0.55	0.31	0.50	**0.49**

Criteria (Goals)	Affordability	Env. Impact	Aesthetics	Const. Duration	Energy savings	Water savings	Priorities
	0.18	0.08	0.18	0.14	0.36	0.06	
ALT 4	0.49	0.50	0.80	0.50	0.90	0.50	**0.70**
ALT 7	0.51	0.50	0.20	0.50	0.10	0.50	**0.30**

Criteria (Goals)	Affordability	Env. Impact	Aesthetics	Const. Duration	Energy savings	Water savings	Priorities
	0.18	0.08	0.18	0.14	0.36	0.06	
ALT 1	0.49	0.50	0.80	0.48	0.50	0.50	**0.55**
ALT 4	0.51	0.50	0.20	0.52	0.50	0.50	**0.45**

Criteria (Goals)	Affordability	Env. Impact	Aesthetics	Const. Duration	Energy savings	Water savings	Priorities
	0.18	0.08	0.18	0.14	0.36	0.06	
ALT 1	0.48	0.50	0.80	0.48	0.90	0.50	**0.69**
ALT 7	0.52	0.50	0.20	0.52	0.10	0.50	**0.31**

Finally, a new set of priorities give more importance to aesthetics and affordability goals. The new priorities resulted in ALT1 being the best option to meet the goals for the project, as shown in Table 23; the options that best fit the solution to the project needs vary according to the goals established by the decision maker.

Table 23. Selection alternatives with new priorities of project goals

RANK	PRIORITIES	PERCENTAGE
1	Affordability	**33.69%**
2	Aesthetics	**32.17%**
3	Water efficiency	**8.87%**
4	Energy efficiency	**8.42%**
5	Const. Duration	**8.42%**
6	Env. Impact	**8.42%**

Criteria (Goals)	**Affordability**	**Env. Impact**	**Aesthetics**	**Const. Duration**	**Energy savings**	**Water savings**	
	0.34	0.08	0.32	0.08	0.08	0.09	**Priorities**
ALT 1	0.49	0.50	0.83	0.48	0.50	0.50	**0.59**
ALT 4	0.51	0.50	0.17	0.52	0.50	0.50	**0.39**

The change in the preferences of the decision maker for the project goals resulted in different priorities for the same alternatives. This result shows the importance of defining the goals from the beginning of the project since the decision-making process is affected by the weight of the project goals.

7.4 Discussions and limitations

The proposed DSS has shown some strengths in the creation and comparison of alternatives at early stages of the pre-construction process. However, it is important to consider the limitations of the model. Given that the scope of the research focuses on single-family homes located in the Greater Atlanta area, the proposed DSS was designed for this type of residential buildings and has not been validated for other types of residential construction. There is limited literature discussing the integration of project goals in traditional projects, and for this reason, the system was tested using a case study from a student design competition where the information about the preferences of the decision makers was available as a result, the system has not being implemented in a traditional project.

The decision-making system has several limitations that are recommended to be addressed in future work. The system was intended to be used by a unitary decision maker considering that this is the case for single-family homes. However, it is recommended to modify the system so it can address the situation of multiple decision makers, which would be the case for multifamily projects. Additionally, the independence of the design goals need further revision given that the definition of the attributes (i.e., social cost of CO2 emissions, energy savings, water savings) tend to overlap, compromising the independence of the objectives.

One major challenge for the research was the creation of the materials database given that the data required is not centralized and standardized. The environmental impacts were limited to CO2 emissions and calculated with the help of life cycle assessment. The proposed DSS is to be used in the early stages of single-family houses where the final project cost, duration, and environmental impact is not available.

CHAPTER 8 CONCLUSION AND FUTURE RESEARCH

8.1 Conclusions

The selection of construction parameters at the early stages of the project delivery is a time-consuming process with an important impact in project outcomes. The previous chapter shows envelope materials selection can represent a reduction in the construction cost. However, it concurrently changes the energy requirements for the entire project resulting in a higher operational cost. The impact of these changes difficult to predict without software that integrates all the systems and the impact of the decisions at the same time.

This research has addressed the research questions presented in Chapter 1. The proposed DSS integrates project goals and project conditions in early stages of the pre-construction process (i.e., pre-design, conceptual design, and schematic design) when the importance and impact of the decisions are high, and the cost of making decisions is low. The proposed system allows the integration of project goal in the selection of sustainable features. The results from the case study showed that the selection of different preferences has an impact over the selection of alternatives.

Aside from cost and energy efficiency, a construction project has multiple goals. This research presents a new paradigm of integrating the preferences of the decision maker in the selection of alternatives. The proposed DSS allows to explore alternatives and review the impact of decisions on building performance, cost, and environmental impact. The best solution is not always the one with the lower construction cost or the highest energy savings. The DSS allows finding a balance between the alternatives and the project goals, as the best alternative changes according to the preferences of the decision maker.

Decision makers without a high level of expertise can use the DSS. The architecture of the DSS fulfills the purpose of guiding the process of selection of parameters for the construction of the alternatives. The use of a database with information about materials, appliances, and systems will reduce the time needed to create an alternative and reduce the errors introduced by calculating procedures and modeling assumptions. The expectation is for the DSS to help the decision maker integrate sustainable parameters in future projects because the system can be used to create multiple alternatives which allow predicting the impact of the decisions made by the decision maker. Additionally, predicting the impact on construction costs and future projections for operational cost can be used to justify better the savings incurred from a decision. Policymakers can also use the DSS to predict the impact of utility rates and incentives on home-owner decisions.

Creating a materials database is time-consuming, and automatization is difficult because the information is not readily available. Design performance depends on many different components sold by different entities and evaluated by multiple agencies. The information associated with one component disseminates through different sources. Generally, the information requires interpretation before being used since universal nomenclature to identify the components is unavailable.

8.2 Future research

The decision support system proposed in this research allows the integration of project goals and the comparison of alternatives in the process of selecting sustainable parameters for single-family housing. The proposed architecture of the system can extend vertically and horizontally. The vertical extension of the DSS refers to the application within the construction industry to more types of residential and commercial buildings, while the horizontal extension refers to other locations.

One of the challenges during the construction of the DSS was information gathering and the creation of the database of materials, appliances, and systems. Storing large information amount in the database requires manual processing. Findings show that the information is not standardized, and this implies that the process of acquiring the information for new components and maintaining the information up to date for existing components is unfit for automatization. Proposing a universal index system is a research opportunity to organize information from different public and private sources (e.g., Energy Star, Department of Energy, NAHB, NREL, R.S. Means, etc.). Ideally, an index system would allow assigning unique codes to individual components to pull information from all the sources that feed the database. Since the task of collecting data for each component is time-consuming and increases the possibility of errors, the creation of a universal system for indexing information will contribute to the reduction of simulation time for the DSS proposed in this research as well as for all the existing software that use the same sources of information.

For future research, it is suggested to include multiple decision makers in the process, as well as analyzing the decision problem under uncertainty, including for example the effects of future changes in the price of materials and utilities and considering incentives and the possibility of selling energy to the grid. Also, the independence of objectives established as design goals should be revised. Additionally, while AHP is included in most operations research and management science textbooks, and the general consensus is that the method is both technically valid and practically useful, the method does have its critics with examples that show that existing decision methods can lead to poor decision making (Hazelrigg, 2003). It is recommend for future research to explore other decision methods and to revise if the selection of alternatives are affected by the use of different decision methodology.

Finally, future research opportunities include the integration of more parameters into the model and the integration with computer-aided design and drafting software like AutoCAD, Sketch-up, and Revit. Furthermore, research opportunities include the creation of new modules for later-phases of the project delivery to allow continuity in the delivery process as the design becomes more defined, which will also improve the accuracy of the cost, time, and environmental impact as the project advances.

APPENDIX A

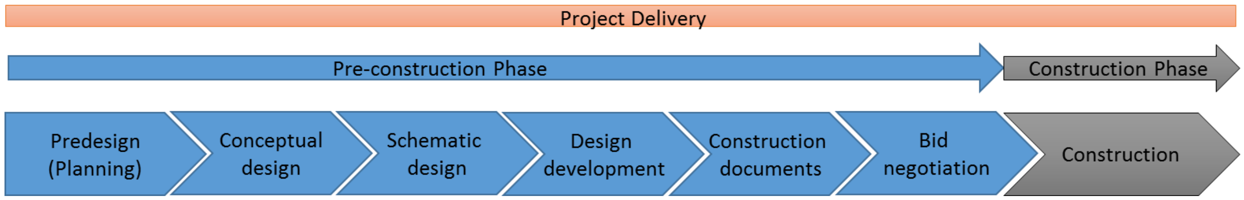
Questions for the semi-structured interview

First interview

1. Please describe the decision-making process that takes place for the design of a residential unit
- Who are the decision makers in this process?
- What is your role in the decision-making process?
- If applicable, please describe how the selection of the following parameters takes place?
    - Location,
    - orientation,
    - building form/geometry,
    - building envelope,
    - arrangement and grouping of spaces,
    - space conditioning,
    - energy efficiency,
    - water efficiency,
    - Renewable energy.

2. Do you use any computational tools to simulate and design residential houses? If so, which ones?

3. How much time does it take to design a residential unit? Please give specific examples that include the unit size in sq. ft., the construction type, and the time in weeks that the pre-construction phase takes as described in the following diagram:



4. Do you have any training in SUSTAINABLE Development practices? Do you hold any sustainable certificate (LEED, NAHB, other Sustainable/Green professional Credential)? If so, which ones?

5. Do you think that is there a market for sustainable homes in the Greater Atlanta Area?

6. Do you think that there is sufficient information available on the added cost of building sustainable homes?
7. What do you believe are the barriers to implementing sustainable parameters in single-family housing?

The following causal loop diagram is proposed to represent the relationships among elements that are part of the selection of sustainable parameters in residential housing (Diagram will be shown during the interview). Do you think that the structure of the model is compared directly with the structure of the real system that the model represents?

8. Do you think that the model aggregation is appropriate and if a model includes all relevant structure? (Boundary-adequacy of the model)

[End of interview]

Second interview

Follow up interview (Second interview after the casual loop diagram have included the suggestions from the first round of interviews)

1. The following System Dynamics model is a proposed tool to analyze system performance under different scenarios. Do you think that the structure of the model is compared directly with the structure of the real system that the model represents?

- Do you think that the model aggregation is appropriate and if a model includes all relevant structure? (Boundary-adequacy of the model)

- Do you think that the model behavior matches the observed behavior of the real system? (Behavior-reproduction test)

2. The following Decision support system is a proposed tool that can be used by decision makers in the selection of sustainable parameters for single-family housing. Do you think that the results from the system match the behavior observed in the real system?

3. Do you think that decision makers can use the results from the system during the early stages of residential development? Please explain your answer.

APPENDIX B

Vensim Functions

(1) APR:INTERPOLATE:

(2) Balance= INTEG (-Principal,Loan Value)

(3) Down payment=House Cost*dpp/100

(4) dpp:INTERPOLATE:

(5) Equity= INTEG (Principal,0)

(6) Financing cost= INTEG (Monthly Interest,0)

(7) House Cost=IHC

(8) IHC:INTERPOLATE:

(9) Loan Value=House Cost-Down payment

(10) Monthly Interest=IF THEN ELSE(Balance>=0,Balance*Monthly interest rate , 0)

(11) Monthly interest rate=APR/12

(12) n=y*12

(13) P=((Loan Value)*(Monthly interest rate*(1+Monthly interest rate)^n))/((1+Monthly interest rate)^n-1)

(14) Principal=IF THEN ELSE(Balance>=P , P-Monthly Interest ,Balance)

(15) y:INTERPOLATE:

(16) Annual expenses=IF THEN ELSE((Time/12)-INTEGER(Time/12)=0, Yearly home expenses, 0)

(17) Annual utilities:INTERPOLATE:

(18) Assessed Value=House Cost*0.4

(19) DTI:INTERPOLATE:

(20) Debt-to-income ratio

(21) Excepted Value=30000

(22) Exemptions=IF THEN ELSE("Owner occupied?"=0, 0, Excepted Value)

(23) Expenses=Monthly home expenses

(24) Given home insurance:INTERPOLATE:

(25) Home insurance=IF THEN ELSE(Given home insurance>0, Given home insurance, House Cost/1000*3.5)

(26) House Cost/1000*3.5

(27) House Cost=IHC

(28) GET XLS CONSTANTS('01 basico para excel con vensim.xls', 'Sheet1' , 'c9')

(29) IHC:INTERPOLATE:

(30) MFI required=Annual expenses/(DTI)

(31) Monthly home expenses=Monthly utilities+(PITI/12)

(32) Monthly utilities=Annual utilities/12

(33) "Owner occupied?"=1

(34) [0,1,1]

(35) P=((Loan Value)*(Monthly interest rate*(1+Monthly interest rate)^n))/((1+Monthly interest rate)^n-1)

(36) PITI=Home insurance+(P*12)+Property taxes

(37) Principal, interest, taxes, and Insurance

(38) Property taxes= ((((0.27+1.2+0.05)*Assessed Value)+(10.28+10.24+0.5+21.64)*(Assessed Value-Exemptions)+0.25*(Assessed Value-2000))/1000)

(39) Total home expenses= INTEG (Annual expenses, 0)

(40) Yearly home expenses= INTEG (Expenses-Annual expenses,0)

(41) Electricity GWP:INTERPOLATE:

(42) Fuel GWP:INTERPOLATE:

(43) Materials GWP:INTERPOLATE:

(44) Natural Gas GWP:INTERPOLATE:

(45) Operating GWP=Electricity GWP+Fuel GWP+Natural Gas GWP

(46) SCCO2:INTERPOLATE:

(47) Social cost of Embodied energy=IF THEN ELSE(Time=0, Materials GWP*SCCO2, 0)

(48) Social Cost of Operating Energy=IF THEN ELSE((Time/12)-INTEGER(Time/12)=0, (Operating GWP*SCCO2), 0)

(49) IF THEN ELSE(Time=0, 0, IF THEN ELSE((Time/12)-INTEGER(Time/12)=0, (Operating GWP*SCCO2), 0))

(50) Total Social Cost of CO2= INTEG (Social cost of Embodied energy+Social Cost of Operating Energy,0)

APPENDIX C

Visual Basic Code

Private Declare Function vensim_be_quiet Lib "vendll32.dll" (ByVal quietflag As Long) As Long

Private Declare Function vensim_check_status Lib "vendll32.dll" () As Long

Private Declare Function vensim_command Lib "vendll32.dll" (ByVal Vcommand $) As Long

Private Declare Function vensim_continue_simulation Lib "vendll32.dll" (ByVal number_time_step As Long) As Long

Private Declare Function vensim_finish_simulation Lib "vendll32.dll" () As Long

Private Declare Function vensim_get_data Lib "vendll32.dll" (ByVal filename $, ByVal varname $, ByVal timename $, varvals As Single, timevals As Single, ByVal maxpoints As Integer) As Long

Private Declare Function vensim_get_dpval Lib "vendll32.dll" (ByVal varname $, varval As Double) As Long

Private Declare Function vensim_get_dpvecvals Lib "vendll32.dll" (vecoff As Long, varvals As Double, ByVal veclen As Long) As Long

Private Declare Function vensim_get_info Lib "vendll32.dll" (ByVal infowanted As Long, ByVal buf $, ByVal maxbuflen As Long) As Long

Private Declare Function vensim_get_sens_at_time Lib "vendll32.dll" (ByVal filename $, ByVal varname $, ByVal timename $, attime As Single, vals As Single, ByVal maxpoint As Long) As Long

Private Declare Function vensim_get_substring Lib "vendll32.dll" (ByVal fullstring $, ByVal frompos As Long, ByVal buf $, ByVal maxbuflen As Long) As Long

Private Declare Function vensim_get_val Lib "vendll32.dll" (ByVal varname $, varval As Single) As Integer

Private Declare Function vensim_get_varattrib Lib "vendll32.dll" (ByVal varname $, ByVal attrib As Long, ByVal buf $, ByVal maxbuflen As Long) As Long

```
Private Declare Function vensim_get_varnames Lib "vendll32.dll" (ByVal filter $ , ByVal vartype As Long, ByVal buf $ , ByVal maxbuflen As Long) As Long
Private Declare Function vensim_get_varoff Lib "vendll32.dll" (ByVal varname $ ) As Long
Private Declare Function vensim_get_vecvals Lib "vendll32.dll" (vecoff As Long, varvals As Single, ByVal nelm As Long) As Long
Private Declare Function vensim_set_parent_window Lib "vendll32.dll" (ByVal vwidnow As Long, ByVal r1 As Long, ByVal r2 As Long) As Long
Private Declare Function vensim_show_sketch Lib "vendll32.dll" (ByVal viewnum As Long, ByVal wantscroll As Long, ByVal zoompercent As Long, ByVal Vwindow As Long) As Long
Private Declare Function vensim_start_simulation Lib "vendll32.dll" (ByVal loadfirst As Integer, ByVal game As Long, ByVal overwrite As Long) As Long
Private Declare Function vensim_tool_command Lib "vendll32.dll" (ByVal Vcommand $ , ByVal Vwindow As Long, ByVal iswip As Long) As Long
```

```
Sub run_finsimulate()
Dim x, result, tpoints As Integer
Dim tval(500) As Single
Dim rval(500) As Single
Workbooks.Open "C:\Users\bcuser\Dropbox\a_Gatech\disertation\00 Modelos\DSS CPR MODEL\2018 II\INTEGRACION 21\parameters for cpr.xls"
result = vensim_command("SPECIAL>LOADMODEL|C:\Users\bcuser\Dropbox\a_Gatech\disertation\00 Modelos\DSS CPR MODEL\2018 II\INTEGRACION 21\01 BASICO PARA EXCEL.vpm")
result = vensim_be_quiet(0)
result = vensim_command("SPECIAL>READCUSTOM|01 BASICO PARA EXCEL.vgf")
If result = 0 Then Exit Sub
```

```
result = vensim_command("SIMULATE>CHGFILE")
result = vensim_command("SIMULATE>DATA")
result = vensim_command("SIMULATE>RUNNAME|orange")
If result = 0 Then Exit Sub
'num $   = Worksheets("Financial").Cells(8, 2).Value
'comstr $   = "SIMULATE>SETVAL|IHC = " + num $
'comstr $   = "SIMULATE>SETVAL|POPULATION INITIAL = " + num $
''result = vensim_command(comstr $  )
'If result = 0 Then Exit Sub
result = vensim_command("MENU>RUN")
If result = 0 Then Exit Sub
tpoints = vensim_get_data("orange.vdf", "Balance", "time", rval(1), tval(1), 400)
For x = 1 To tpoints
  Worksheets("Financial").Cells(x + 27, 9).Value = tval(x)
  Worksheets("Financial").Cells(x + 27, 10).Value = rval(x)
   Next

End Sub
```

```
Sub Simular_CPR()
ruta = ActiveWorkbook.Path
'Version = Val(Application.Version)
simulation = "apple"
' name given to simulation

'update the parameters from CPR file to parameters
Workbooks.Open filename:=ruta & "\Par_CPR.xls", UpdateLinks:=3
ActiveWorkbook.Save
ActiveWorkbook.Close
```

```
'Generate a vdf file from the xls file and the frm file
result = vensim_command("MENU>XLS2VDF|Par_CPR.xls|DEL_CPRdata.vdf|CPR_form.frm")

'Add data to Vensim and Simulate
result = vensim_command("SIMULATE>ADDDATA|DEL_CPRdata.vdf")
If result = 0 Then Exit Sub
result = vensim_command("SIMULATE>DATA|DEL_CPRdata")
If result = 0 Then Exit Sub

'SIMULATE CPR using the simulation name declared as "simulation"
result = vensim_command("special>loadmodel|" & ruta & "\01 BASICO PARA EXCEL.vpm")
'result = vensim_command("SIMULATE>RUNNAME|? Choose a name for the simulation")
result = vensim_command("SIMULATE>RUNNAME|" & simulation)
If result = 0 Then Exit Sub
result = vensim_command("MENU>RUN|O")
If result = 0 Then Exit Sub

'EXPORT results to CPR
result = vensim_command("MENU>VDF2XLS|!|DEL_CPRresults.xls|CPR_list.lst|*|")
'result = vensim_command("MENU>VDF2XLS|" & simulacion2 & ".vdf|Results.xls|List_" & ActiveSheet.Name & ".lst|*|1")
If result = 0 Then Exit Sub
Workbooks.Open filename:=ruta & "\DEL_CPRresults.xls"

'Range("A1").Select
    'Range(Selection, Selection.End(xlDown)).Select
    'Range(Selection, Selection.End(xlToRight)).Select
```

```
    'Selection.Copy
    'Windows("CPR.xls").Activate
    'Sheets("RESULTS").Select
    'ActiveWindow.SmallScroll Down:=-112
    'Range("A1").Select
    'ActiveSheet.Paste
    'Windows("DEL_CPRresults.xls").Activate
  'Application.CutCopyMode = False
'ActiveWindow.Close


End Sub
```

REFERENCES

Abdelhamid, T., El-Gafy, M., & Salem, O. (2008). Lean construction: Fundamentals and principles. *American professional constructor journal, 4*, 8-19.

Alexander, M. (2012). Decision-making using the analytic hierarchy process (AHP) and SAS/IML. *Available from (Last checked 28th July 2014).*

Attia, S., Gratia, E., De Herde, A., & Hensen, J. L. (2012). Simulation-based decision support tool for early stages of zero-energy building design. *Energy and Buildings, 49*, 2-15.

Augenbroe, G., de Wilde, P., Moon, H. J., & Malkawi, A. (2004). An interoperability workbench for design analysis integration. *Energy and Buildings, 36*(8), 737-748.

Bambrook, S., Sproul, A., & Jacob, D. (2011). Design optimization for a low energy home in Sydney. *Energy and Buildings, 43*(7), 1702-1711.

Becchio, C., Guglielmino, D., Fabrizio, E., & Filippi, M. (2011). Whole cost analysis of building envelope technologies according to the European Standard EN 15459. *Climamed, 11*, 291-306.

Behdani, B. (2012). *Evaluation of paradigms for modeling supply chains as complex socio-technical systems.* Paper presented at the Simulation Conference (WSC), Proceedings of the 2012 Winter.

Bernstein, H. M., & Russo, M. A. (2014). Green Homes Show Growth in a Recovering Market According to New Report from McGraw Hill Construction. *Energy Design Update, 34*(8), 6-7.

Biaou, A., Bernier, M., & Ferron, Y. (2006). Simulation of zero net energy homes. *Journée thématique du, 21*.

Bolling, A. L., & Mathias, J. A. (2008). Investigation of optimal heating and cooling systems in residential buildings.

Brahme, R., Mahdavi, A., Lam, K., & Gupta, S. (2001). *Complex building performance analysis in the early stages of design.* Paper presented at the Seventh International IBPSA Conference.

Brundtland, G., Khalid, M., Agnelli, S., Al-Athel, S., Chidzero, B., Fadika, L., . . . de Botero, M. M. (1987). Our Common Future (\'Brundtland report\').

Burt, M. R. (2001). *Helping America's homeless: Emergency shelter or affordable housing?* : The Urban Insitute.

Cabała, P. (2010). Using the analytic hierarchy process in evaluating decision alternatives. *Operations research and decisions, 20*(1), 5-23.

Castro-Lacouture, D., & Ramkrishnan, K. (2008). Fuzzy logic method for measuring building quality. *Journal of Quality, 15*(2), 117-129.

Chapman, R. J. (1998). The role of system dynamics in understanding the impact of changes to key project personnel on design production within construction projects. *International Journal of Project Management, 16*(4), 235-247.

Clarke, J., Hong, J., Kim, J., Strachan, P., Hwang, I., & Lee, H. (2005). *Simulation-based design procedure to evaluate hybrid renewable energy systems for residential buildings in Korea.* Paper presented at the Proceedings of 9th International IBPSA Conference.

Crowley, S. (2003). The affordable housing crisis: Residential mobility of poor families and school mobility of poor children. *Journal of Negro Education*, 22-38.

da Luz Reis, A. T., & Lay, M. C. D. (2010). Internal and external aesthetics of housing estates. *Environment and Behavior*, *42*(2), 271-294.

de Wilde, P., & Van Der Voorden, M. (2004). Providing computational support for the selection of energy saving building components. *Energy and Buildings, 36*(8), 749-758.

Ding, G. K. (2008). Sustainable construction—The role of environmental assessment tools. *Journal of environmental management*, *86*(3), 451-464.

Dodge, D. A. N. (2017). Green Multifamily and Single Family Homes 2017.

Downs, A. (2004). *Growth management and affordable housing: do they conflict?* : Brookings Institution Press.

Drake, P. R. (1998). Using the analytic hierarchy process in engineering education. *International Journal of Engineering Education*, *14*(3), 191-196.

EIA. (2016). Residential energy consumption survery (RECS), 2015. https://www.eia.gov/consumption/residential/data/2015/index.php?view=characteristics

EIA. (2018). How much energy is consumed in residential and commercial buildings? Retrieved from http://www.eia.gov/tools/faqs/faq.cfm?id=86&t=1

Energy Star, E. (2018). Product Specifications & Partner Commitments Search. Retrieved 09/05/2018

EPA. (2016). *Best Practices to Consider When Evaluating Water Conservation and Efficiency as an Alternative for Water Supply Expansion*. Retrieved from US Washington, DC 20460: https://www.epa.gov/sites/production/files/2016-12/documents/wc_best_practices_to_avoid_supply_expansion_2016_508.pdf

Esbensen, T. V., & Korsgaard, V. (1977). Dimensioning of the solar heating system in the zero energy house in Denmark. *Solar Energy, 19*(2), 195-199.

Farlex, D. (2016, Feb 17). Public Utilities. Retrieved from http://legal-dictionary.thefreedictionary.com/Public+Utilities

Ferrara, M., Fabrizio, E., Virgone, J., & Filippi, M. (2014). A simulation-based optimization method for cost-optimal analysis of nearly Zero Energy Buildings. *Energy and Buildings, 84*, 442-457.

Fischer, M., & Tatum, C. (1997). Characteristics of design-relevant constructability knowledge. *Journal of Construction Engineering and Management*, *123*(3), 253-260.

Francescato, G., Weidemann, S., Anderson, J. R., & Chenoweth, R. (1979). *Residents' satisfaction in HUD-assisted housing: Design and management factors* (Vol. 390): The Office.

Gambatese, J. A., Pocock, J. B., & Dunston, P. S. (2007). *Constructability concepts and practice*.

Ganiç, N., & Yılmaz, A. Z. (2014). Adaptation of the cost optimal level calculation method of Directive 2010/31/EU considering the influence of Turkish national factors. *Applied Energy*, *123*, 94-107.

Geddes, R. (1998). Public utilities. *The Encyclopedia of Law and Economics*.

Gossard, D., Lartigue, B., & Thellier, F. (2013). Multi-objective optimization of a building envelope for thermal performance using genetic algorithms and artificial neural network. *Energy and Buildings, 67*, 253-260.

Guggemos, A. A., & Horvath, A. (2006). Decision-support tool for assessing the environmental effects of constructing commercial buildings. *Journal of Architectural Engineering, 12*(4), 187-195.

Gustavsson, L., & Joelsson, A. (2010). Life cycle primary energy analysis of residential buildings. *Energy and Buildings, 42*(2), 210-220.

Haettenschwiler, P. (2001). Neues anwenderfreundliches konzept der entscheidungsunterstützung. *Zurich, vdf Hochschulverlag AG*, 189-208.

Hamdy, M., Hasan, A., & Siren, K. (2011). Applying a multi-objective optimization approach for design of low-emission cost-effective dwellings. *Building and Environment, 46*(1), 109-123.

Hamdy, M., Hasan, A., & Siren, K. (2013). A multi-stage optimization method for cost-optimal and nearly-zero-energy building solutions in line with the EPBD-recast 2010. *Energy and Buildings, 56*, 189-203.

Harris, D. J. (1999). A quantitative approach to the assessment of the environmental impact of building materials. *Building and Environment, 34*(6), 751-758.

Hasan, A., Vuolle, M., & Sirén, K. (2008). Minimisation of life cycle cost of a detached house using combined simulation and optimisation. *Building and Environment, 43*(12), 2022-2034.

Hazelrigg, G. A. (2003). Validation of engineering design alternative selection methods. *Engineering Optimization, 35*(2), 103-120.

Hendricx, A. (2000). *A core object model for architectural design*.

HG. org. (2010, May 22). Legal dictionary. Retrieved from http://legal-dictionary.thefreedictionary.com/Public+Utilities

Hjorth, P., & Bagheri, A. (2006). Navigating towards sustainable development: A system dynamics approach. *Futures, 38*(1), 74-92.

Home Depot, H. (2019). Shop search results.

Hwang, B. G., & Tan, J. S. (2012). Green building project management: obstacles and solutions for sustainable development. *Sustainable Development, 20*(5), 335-349.

Ibbs, W., & Liu, M. (2005). System dynamic modeling of delay and disruption claims. *Cost Engineering, 47*(6), 12-15.

India Habitat Centre. (2006). *In pursuit of sustainable development: Mainstreaming environment in the construction sector*. Retrieved from New Delhi:

Interagency Working Group, I. (2013). Technical update on the social cost of carbon for regulatory impact analysis-under executive order 12866. *Interagency Working Group on Social Cost of Carbon, United States Government*.

Interagency Working Group on Social Cost of Carbon, I. (2010). Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866. In U. S. Government (Ed.), *INSTITUTIONAL INERTIA AND THE SOCIAL COST OF CARBON* (Vol. 104, pp. 551).

Iwaro, J., Mwasha, A., Williams, R. G., & Wilson, W. (2014). An integrated approach for sustainable design and assessment of residential building envelope: part I. *International Journal of Low-Carbon Technologies*, ctu002.

Jadid, M. N., & Badrah, M. K. (2012). *Decision support system approach for construction materials selection.* Paper presented at the Proceedings of the 2012 Symposium on Simulation for Architecture and Urban Design.

Jéquier, E., & Constant, F. (2009). Water as an essential nutrient: the physiological basis of hydration. *European Journal Of Clinical Nutrition*, *64*, 115.

Jergeas, G., & Put, J. V. d. (2001). Benefits of constructability on construction projects. *Journal of Construction Engineering and Management, 127*(4), 281-290.

Keeney, R. L., & Raiffa, H. (1993). *Decisions with multiple objectives: preferences and value trade-offs*: Cambridge university press.

Kibert, C. J. (1994). *Establishing principles and a model for sustainable construction* Paper presented at the Proceedings of the First International Conference on Sustainable Construction of CIB TG.

Kim, J.-H., Augenbroe, G., & Suh, H.-S. (2013). *Comparative study of the leed and ISO-CEN building energy performance rating methods.* Paper presented at the 13th conference of international building performance association, France.

Kim, J. H. (2016). *The impact of occupant modeling on energy outcomes of building energy simulation.* Georgia Institute of Technology.

Kurnitski, J., Saari, A., Kalamees, T., Vuolle, M., Niemelä, J., & Tark, T. (2011). Cost optimal and nearly zero (nZEB) energy performance calculations for residential buildings with REHVA definition for nZEB national implementation. *Energy and Buildings, 43*(11), 3279-3288.

Lam, P. T., Chan, E. H., Chau, C., Poon, C., & Chun, K. (2009). Integrating green specifications in construction and overcoming barriers in their use. *Journal of Professional Issues in Engineering Education and Practice, 135*(4), 142-152.

Lang, J. T. (1987). *Creating architectural theory: The role of the behavioral sciences in environmental design*: Van Nostrand Reinhold New York.

Lee, S., & Peña-Mora, F. (2005). *System dyanmics approach for error and change management in concurrent design and construction.* Paper presented at the Proceedings of the 37th conference on Winter simulation.

Lenoir, A., Garde, F., & Wurtz, E. (2011). Zero Energy Buildings in France: Overview and Feedback. *ASHRAE Transactions, 117*(2).

Linneman, P. D., & Megbolugbe, I. F. (1992). Housing affordability: Myth or Reality? *Urban Studies, 29*(3/4), 369-392.

Lorenz, T., & Jost, A. (2006). *Towards an orientation framework in multi-paradigm modeling.* Paper presented at the Proceedings of the 24th International Conference of the System Dynamics society.

Love, P., Holt, G., Shen, L., Li, H., & Irani, Z. (2002). Using systems dynamics to better understand change and rework in construction project management systems. *International Journal of Project Management, 20*(6), 425-436.

Luna-Reyes, L. (2003). Collaboration, trust, and knowledge sharing in information-technology-intensive projects in the public sector (New York).

Marzouk, M., Abdelhamid, M., & Elsheikh, M. (2013). SELECTING SUSTAINABLE BUILDING MATERIALS USING SYSTEM DYNAMICS AND ANT COLONY OPTIMIZATION. *Journal of Environmental Engineering and Landscape Management, 21*(4), 237-247. doi:10.3846/16486897.2013.788506

Matsumoto, H. (1999). *System dynamics model for life cycle assessment (LCA) of residential buildings.* Paper presented at the Proceedings of The Third International IBPSA Conference (Building Simulation 1999), Sep.

McLennan, J. F. (2004). *The philosophy of sustainable design: The future of architecture*: Ecotone publishing.

Meadows, D. H. (1989). System dynamics meets the press. *System Dynamics Review, 5*(1), 69-80.

Menassa, C. C., Peña-Mora, F., & Pearson, N. (2009). Option Pricing Model to Analyze Cost–Benefit Trade-Offs of ADR Investments in AEC Projects. *Journal of Construction Engineering and Management, 135*(3), 156-168.

Meryman, H., & Silman, R. (2004). Sustainable engineering–using specifications to make it happen. *Structural engineering international, 14*(3), 216-219.

Morley, R. (2006). The Death of American Manufacturing. *The Trumpet, 17*.

Moselhi, O., Gong, D., & El-Rayes, K. (1997). Estimating weather impact on the duration of construction activities. *Canadian Journal of Civil Engineering, 24*(3), 359-366.

NAHB, National Association of Home Builders. (2015). Eye on Housing: How long does it take to build a Single-family home? Retrieved from http://eyeonhousing.org/2015/08/how-long-does-it-take-to-build-a-single-family-home/

National Institute of Building Sciences. (2007). Assessment to the US Congress and US Department of Energy on HIGH PERFORMANCE BUILDINGS.

National Renewable Energy Laboratory, N. (2012). U.S. Life Cycle Inventory Database. Retrieved from https://www.lcacommons.gov/nrel/search

National Renewable Energy Laboratory, N. (2018). National residential efficiency measure database. Retrieved 01/08/2018 https://remdb.nrel.gov/

Newbold, S., Griffiths, C., Moore, C., Wolverton, A., & Kopits, E. (2010). *The "social cost of carbon" made simple*. Retrieved from

Ng, H. S., Peña-Mora, F., & Tamaki, T. (2007). Dynamic conflict management in large-scale design and construction projects. *Journal of Management in Engineering, 23*(2), 52-66.

Norton, P., & Christensen, C. (2007). *Performance Results from a Cold Climate Case Study for Affordable Zero Energy Homes: Preprint*. Retrieved from

O'Connor, J. T., Rusch, S. E., & Schulz, M. J. (1987). Constructability concepts for engineering and procurement. *Journal of Construction Engineering and Management*, *113*(2), 235-248.

O'Dell, W., Smith, M. T., & White, D. (2004). Weaknesses in current measures of housing needs. *Housing and Society, 31*(1), 29-40.

Ogunlana, S. O., Li, H., & Sukhera, F. A. (2003). System dynamics approach to exploring performance enhancement in a construction organization. *Journal of Construction Engineering and Management*, *129*(5), 528-536.

Onat, N. C., Egilmez, G., & Tatari, O. (2014). Towards greening the U.S. residential building stock: A system dynamics approach. *Building and Environment, 78*, 68-80. doi:10.1016/j.buildenv.2014.03.030

Ozcan-Deniz, G. (2011). *An integrated multi-agent framework for optimizing time, cost and environmental impact of construction processes.* Florida International University.

Passive House Institute. (2016). Criteria for the Passive House, EnerPHit and PHI Low Energy Building Standard. Retrieved from http://www.passiv.de/downloads/03_building_criteria_en.pdf

Passive House Institute. (2016). Multifamily Resource Center. *5 Passive Building Principles.* Retrieved from http://multifamily.phius.org/service-category/5-passive-building-principles

Peña-Mora, F., & Li, M. (2001). Dynamic planning and control methodology for design/build fast-track construction projects. *Journal of Construction Engineering and Management*, *127*(1), 1-17.

Peterson, K., Torcellini, P., Grant, R., Taylor, C., Punjabi, S., Diamond, R., . . . Kennett, E. (2015). A Common Definition for Zero Energy Buildings. US Department of energy. *Energy Efficiency and Renewable Energy*.

Power, D. (2002). Decision Support Systems: Concepts and Resources for Managers. *Studies in Informatics and Control, 11*(4), 349-350.

Purdy, J., & Beausoleil-Morrison, I. (2001). *The significant factors in modelling residential buildings.* Paper presented at the Seventh International IBPSA Conference, RIo de Janeiro, Brazil, August 13.

Qi, G., Shen, L., Zeng, S., & Ochoa J, J. (2010). The drivers for contractors' green innovation: an industry perspective. *Journal of Cleaner Production, 18*(14), 1358-1365.

R. S. Means Company, R. M. (2017). Square foot costs with RSMeans data. *Square foot costs with RSMeans data.*

R.S. Means Company, R. M. (2017). Residential costs with RSMeans data. *Residential costs with RSMeans data.*

Rich, E. H. (2003). Modeling the dynamics of organizational knowledge.

Robichaud, L. B., & Anantatmula, V. S. (2010). Greening project management practices for sustainable construction. *Journal of Management in Engineering, 27*(1), 48-57.

Robinson, S. (2004). *Simulation: the practice of model development and use*: Wiley Chichester.

Saaty, T. L. (1994). How to make a decision: the analytic hierarchy process. *Interfaces, 24*(6), 19-43.

Saaty, T. L. (2008). Relative measurement and its generalization in decision making why pairwise comparisons are central in mathematics for the measurement of intangible factors the analytic hierarchy/network process. *Revista de la Real Academia de Ciencias Exactas, Fisicas y Naturales. Serie A. Matematicas*, *102*(2), 251-318.

Saaty, T. L., & Peniwati, K. (2013). *Group decision making: drawing out and reconciling differences*: RWS publications.

Sartori, I., & Hestnes, A. G. (2007). Energy use in the life cycle of conventional and low-energy buildings: A review article. *Energy and Buildings, 39*(3), 249-257.

Schwartz, M., & Wilson, E. (2008). Who can afford to live in a home?: A look at data from the 2006 American Community Survey. *US Census Bureau*.

Senge, P. M., & Forrester, J. W. (1980). Tests for building confidence in system dynamics models. *System dynamics, TIMS studies in management sciences, 14*, 209-228.

Shen, L., Wu, Y., Chan, E., & Hao, J. (2005). Application of system dynamics for assessment of sustainable performance of construction projects. *Journal of Zhejiang University Science A, 6*(4), 339-349.

Shen, T.-S. (2005). ESM: a building evacuation simulation model. *Building and Environment, 40*(5), 671-680.

Shi, Q., Zuo, J., Huang, R., Huang, J., & Pullen, S. (2013). Identifying the critical factors for green construction - an empirical study in China. *Habitat international, 40*, 1-8.

Smith, J., & Love, P. E. D. (2004). Stakeholder Management during Project Inception: Strategic Needs Analysis. *Journal of Architectural Engineering, 10*(1), 22-33. doi:doi:10.1061/(ASCE)1076-0431(2004)10:1(22)

Stamps, A. (2013). *Psychology and the aesthetics of the built environment*: Springer Science & Business Media.

Thompson, B. P., & Bank, L. C. (2010). Use of system dynamics as a decision-making tool in building design and operation. *Building and Environment, 45*(4), 1006-1015. doi:10.1016/j.buildenv.2009.10.008

Tomkiewicz, H. S. (2011). Barriers to Implementation of Sustainable Construction Practices in the Homebuilding Industry: A Case Study of Rochester, NY.

Torcellini, P., Pless, S., Deru, M., & Crawley, D. (2006). Zero energy buildings: a critical look at the definition. *National Renewable Energy Laboratory and Department of Energy, US*.

U.S. Department of Energy. (2012). DOE Challenge Home Label Methodology.

U.S. Department Of Energy. (2014, January 20, 2014). Climate Zones. Retrieved from http://energy.gov/eere/buildings/climate-zones

U.S. Department of Energy. (2017). 2017 U.S. Department of Energy Race to Zero Student Design Competition Guide.

U.S. Energy Information Administration. (2016). Data: Annual Energy Review (Vol. 2016).

United Nations. (2013). *Global Sustainable Development Report – Executive Summary: Building the Common Future We Want*. Retrieved from

US Green Building Council. (2010). LEED® for Homes Rating System Multifamily Mid-Rise| October 2010. *LEED For Homes Rating System Multifamily Mid-Rise-October 2010*.

US Green Building Council. (2003). Building Momentum. *National Trends and Prospects for High-Performance Green Buildings, Washington, DC*.

USGBC. (2014). *Leed in motion: Residential*. Retrieved from

Wall, M. (2006). Energy-efficient terrace houses in Sweden: Simulations and measurements. *Energy and Buildings, 38*(6), 627-634.

Wallace, J. E. (1995). Financing affordable housing in the United States. *Housing Policy Debate, 6*(4), 785-814.

Wallbaum, H., Ostermeyer, Y., Salzer, C., & Escamilla, E. Z. (2012). Indicator based sustainability assessment tool for affordable housing construction technologies. *Ecological Indicators, 18,* 353-364.

Wang, L., Gwilliam, J., & Jones, P. (2009). Case study of zero energy house design in UK. *Energy and Buildings*, *41*(11), 1215-1222.

Williams, K., & Dair, C. (2007). What is stopping sustainable building in England? Barriers experienced by stakeholders in delivering sustainable developments. *Sustainable Development, 15*(3), 135-147. doi:10.1002/sd.308

Wilson, J. L., & Tagaza, E. (2006). Green buildings in Australia: drivers and barriers. *Australian Journal of Structural Engineering, 7*(1), 57-63.

Xu, Z., & Coors, V. (2012). Combining system dynamics model, GIS and 3D visualization in sustainability assessment of urban residential development. *Building and Environment, 47*, 272-287. doi:10.1016/j.buildenv.2011.07.012

Yudelson, J. (2008). *The green building revolution*: Island Press.

Yun, J., Back, N., & Yu, C. (2003). *Design and Analysis of KIER Zero Energy Solar House.* Paper presented at the Proc. ISES Solar World Congress.

Zhang, X., Shen, L., Wu, Y., & Qi, G. (2011). Barriers to implement green strategy in the process of developing real estate projects. *The Open Waste Management Journal, 4*(1).

Znouda, E., Ghrab-Morcos, N., & Hadj-Alouane, A. (2007). Optimization of Mediterranean building design using genetic algorithms. *Energy and Buildings, 39*(2), 148-153.